EFTF

20-23 April 2026
Noordwijk, Netherlands

39th European Frequency and Time Forum 2026

Technical Sponsors

sfmc

UFFC
IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society

Organized by esa

PROGRAM

20-23 APRIL 2026 - **Noordwijk,** The Netherlands
NH Conference Centre Leeuwenhorst

For Additional Info Visit: **EFTF2026.org**

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Booklet Rev. 4

Welcome to EFTF 2026

The European Frequency and Time Forum (EFTF) is an international conference and exhibition dedicated to recent advances and emerging trends in scientific research and industrial development in the fields of Frequency and Time.

We are delighted to welcome you to the 39th edition of EFTF, organised by the European Space Agency (ESA).

In line with the long-standing tradition of the conference, a comprehensive programme of tutorials, plenary and invited presentations, together with parallel oral and poster sessions, offers participants a broad and up-to-date overview of the state of the art. The conference is hosted at the Leeuwenhorst Conference Centre in Noordwijk, the Netherlands, close to the ESA–ESTEC campus and in the heart of the Bollenstreek region, renowned for its tulip fields at their peak during the month of April.

A rich programme of social events and a dedicated exhibition area further provide valuable opportunities to renew friendships with colleagues, engage with customers, meet students, and establish new collaborations.

We are confident that EFTF 2026 will be stimulating, rewarding, and truly meaningful.

General Chairs on behalf of the EFTF 2026 Local Organising Committee

Marco Belloni

Jörg Hahn

Organisers

General Conference Chairs
Marco Belloni - European Space Agency – ESA- ESTEC, The Netherlands
Jörg Hahn - European Space Agency, ESA-ESTEC, The Netherlands

Scientific Chair
Jérôme Lodewyck - LTE, Observatoire de Paris, France

Academic Chair
Rachel Godun - NPL—National Physical Laboratory, UK

Tutorial Chair
Filippo Levi – INRIM – Italy

Exhibition Chair
Ronald Holzwarth – Menlo Systems – Germany

Award Chair
Per-Olof Hedekvist – SP-RISE – Sweden

Local Organising Committee
Elizabeth Laier English - European Space Agency – ESA- ESTEC, The Netherlands
Sinda Mejri - European Space Agency – ESA- ESTEC, The Netherlands
Sophio Pataraia - European Space Agency – ESA- ESTEC, The Netherlands
Cedric Plantard - European Space Agency – ESA- ESTEC, The Netherlands
Bernardino Quaranta - European Space Agency – ESA- ESTEC, The Netherlands
Paride Testani - European Space Agency – ESA- ESTEC, The Netherlands
Angelika Kochajkiewicz – ESA Graduate Trainee - ESA- ESTEC, The Netherlands
Katia Berr – ESA Graduate Trainee - ESA- ESTEC, The Netherlands

Arianna Ricchiuti – Event Project Manager | ESA Conference Bureau
Tessa Rowbottom - ESA Conference Bureau
Jasmijn Willemse - ESA Conference Bureau

Scientific Committee
Group 1 : Materials, Resonators, and Resonator Circuits
Marie Bousquet (vice-chair)
Thomas Baron
Matteo Rinaldi
Mario De Miguel
Marc Faucher
Raphaël Levy
Ming-Huang Li

Group 2 : Oscillators, Synthesizers, Noise, and Circuit Techniques
Claudio Calosso (vice-chair)
Attila Kinali
Bichoy Bahr
Javier Serrano
Jean-Michel Friedt
Jeremy Everard
Maxim Goryachev
Michele Giunta
Radan Slavik
Volodymyr Kudriashov

Wan-Thai Hsu

Group 3 : Microwave Frequency Standards
James Camparo (vice-chair)
Mohsin Haji
Christoph Affolderbach
Salvatore Micalizio
Poonam Arora
Songbai Kang
Daniele Monahan

Group 4 : Sensors and Transducers
Joshua Lee (vice-chair)
Jerome Juillard
Giacomo Langfelder
Guillermo Villanueva
Tomas Manzaneque Garcia
Chun Zhao
Michael Schneider

Group 5 : Timekeeping, T&F Transfer, Telecom and GNSS applications
Per Olof Hedekvist (vice-chair)
Sinda Mejri
Anne Amy-Klein
Miho Fujieda
Jerome Delporte
Sascha Schediwy
Huang-Tien Lin
Bernardino Quaranta
Qi Shen
Myoung-Sun Heo
Kun Liang
Judah Levine
Michael Coleman
Ilaria Sesia
Dirk Piester
Jochen Kronjaeger
Jian Yao
Michael Wouters
Pascale Defraigne

Group 6 : Optical Frequency Standards and Applications
Sören Dörscher (vice-chair)
Rachel Godun
Pierre Dubé
Thomas Südmeyer
Tanja Mehlstaeubler
Nicola Poli
Masami Yasuda
Jennifer Black
Won-Kyu Lee
Ronald Holzwarth
Bess Fang
Yige Lin

Sponsors

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Standard Sponsors

Welcome Reception Sponsors

Student Night Sponsors

Coffee Break Sponsors

General Information – Conference App

We are pleased to inform you that the Mobile app for the **EFTF 2026 Conference** is available (**The Event App by EventsAir)**. The App is available for Android and IoS and can be downloaded from PlayStore© and AppStore©.

The App runs on your smart phone or tablet, and provides a great selection of ways for you to plan your meeting experience.

You will be able to:

- View the program
- Download the technical content
- Create your own Agenda
- Access information on directions & entrance procedure
- Communicate and exchange messages with other registered participants
- Search for Attendees

Once installed the EventApp© use the code **EFTF26** to access to the Conference space.

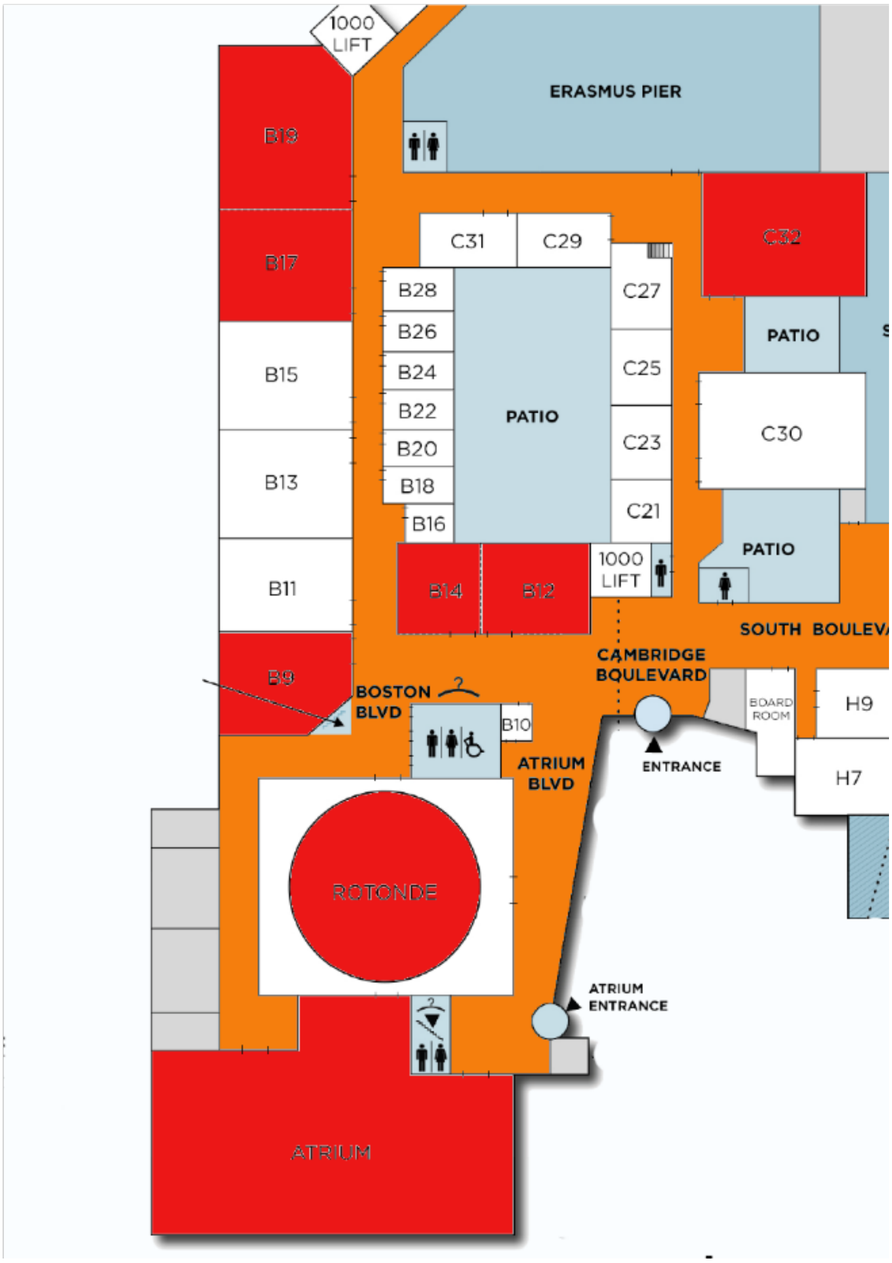
To access the App, please log in using the **email address used for your conference registration** and the **PIN code** that you should have received at the same email address prior to the start of the conference.

If you experience any difficulty retrieving your PIN code, please contact the **Conference Desk** for assistance.

General Information – Conference Venue

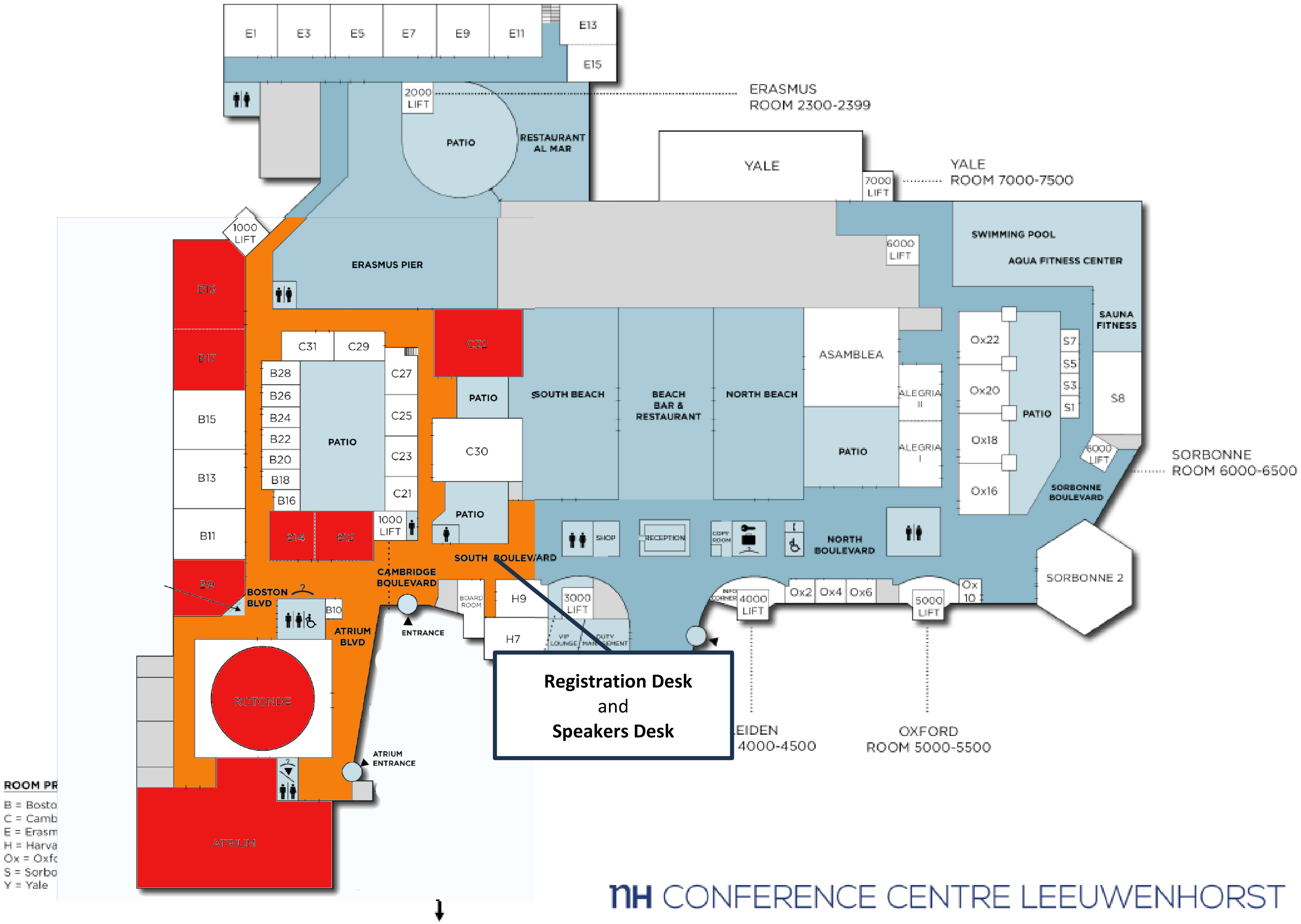
NH Conference Centre Leeuwenhorst - Langelaan 3 2211 XN Noordwijkerhout.

Conference Plant



Registration Desk and Speakers Desk are in south Boulevar

Rotonde	Plenary and Break-out sessions
B17-B19	Break-out sessions
C32	Break-out sessions
B12-B14	Student Posters
B9	Poster Area
Atrium	Exhibitors and Poster Area
C23	Splinter Meeting Room


E1
E3
E5
E7
E9
E11
E13
E15
2000 LIFT
ERASMUS
ROOM 2300-2399
PATIO
RESTAURANT AL MAR
YALE
7000 LIFT
YALE
ROOM 7000-7500
1000 LIFT
ERASMUS PIER
6000 LIFT
SWIMMING POOL
AQUA FITNESS CENTER
SAUNA FITNESS
B19
B17
B15
B13
B11
B9
C31
C29
C32
B28
B26
B24
B22
B20
B18
B16
PATIO
C27
C25
C23
C21
PATIO
C30
SOUTH BEACH
BEACH BAR & RESTAURANT
NORTH BEACH
ASAMBLEA
ALEGRIA II
ALEGRIA I
PATIO
Ox22
Ox20
Ox18
Ox16
PATIO
S7
S5
S3
S1
S8
6000 LIFT
SORBONNE
ROOM 6000-6500
SORBONNE BOULEVARD
B14
B12
1000 LIFT
PATIO
SOUTH BOULEVARD
SHOP
RECEPTION
NORTH BOULEVARD
SORBONNE 2
CAMBRIDGE BOULEVARD
BOSTON BLVD
B10
ATRIUM BLVD
ENTRANCE
BOARD ROOM
H9
H7
3000 LIFT
VIP LOUNGE
DUTY MANAGEMENT
4000 LIFT
Ox2
Ox4
Ox6
5000 LIFT
Ox 10
Registration Desk
and
Speakers Desk
LEIDEN
4000-4500
OXFORD
ROOM 5000-5500
ROTONDE
ATRIUM ENTRANCE
ATRIUM
ROOM PR
B = Bosto
C = Camb
E = Erasm
H = Harva
Ox = Oxfo
S = Sorbo
Y = Yale
nH CONFERENCE CENTRE LEEUWENHORST

General Information - Others

PLEASE NOTE: the conference registration does not include dinners at the hotel. To avoid disappointment, we strongly recommend that you reserve your spot for dinner at the Hotel Restaurant well in advance, due to the tourist season. Reservations can be made via mail *nhleeuwenhorst@nh-hotels.com* or by telephone: *+31 252-378888*, *dial 4*. If the restaurant is fully booked, the reception can recommend several nice beach restaurants.

WiFi at the Conference Centre

Wifi is available free of charge in the conference centre.

User name: nh
Password: wifi

- Log in using landing page
- Bandwidth up to 4Mb/s down and 2Mb/s up
- Data traffic up to 100 MB per session
- VPN is not supported

Transportations

The following trasportations are included in the Conference package:

1) **Monday 20, Tutorials and Welcome Reception**:

- bus from NH Leeuwenhorst to ESTEC, Pick up 7:45 (*For tutorial attendees only*)
- bus from NH Leeuwenhorst to ESTEC, Pick up 8:05 (*For tutorial attendees only*)
- bus from NH Leeuwenhorst to Space Expo, Pick up 17:45 (*For people registered to the Welcome Reception*)
- bus from Space Expo to Noordwijk (Alexander Hotel) to NH Leeuwenhorst, Pick up 21:00

2) **Wednesday 22, Gala Dinner**:

- buses for NH Leeuwenhorst to Louwman Museum, Pick up time 18:00
- buses for Louwman Museum to Noordwijk (Alexander Hotel) to NH Leeuwenhorst, Pick up time 23:00

3) **Friday 24, events**:

- **Satellite Meeting** (*For people registered to the event only)*
  - bus from NH Leeuwenhorst to ESTEC, pick-up time 7:45
  - bus from NH Leeuwenhorst to ESTEC, pick up time 8:05.
- **Delft Visit**:
  - bus from NH Leeuwenhorst to ESTEC to VSC (Delft), pick-up time 13:30 (from NH Leeuwenhorst)
  - bus from VSC (Delft) to Leiden train station to NH Leeuwenhorst, pick up at 17:00
- **ESTEC Visit**:
  - bus from NH Leeuwenhorst to ESTEC (Space Expo), pick-up time 9:30
  - bus from NH Leeuwenhorst to ESTEC (Space Expo), pick-up time 13:30

Public transportation

The Netherlands has a highly effective public transport network. You can plan your journey using the following useful website.

https://9292.nl/en/

Qbuzz streekBuzz Bus 22 stops in front of the Conference Centre.

Note: *Public transport in the Netherlands is efficient, comfortable and accessible for everyone. This means that people with a disability can also easily use these forms of transportation. Finally, you can rent an OV-fiets (rental bike) at train stations. This is a useful option for shorter distances and you don't have to depend on tram or bus schedules. The Netherlands is famous for its cycling culture, and our safe, extensive network of cycling paths makes getting around a breeze.*

Reaching the Conference Centre by car

On-site parking is available for free. Parking cannot be reserved.

Social Events

Monday 20 April 2026 – 18:00 to 21:00 - Welcome Reception - Space Expo

Kick off EFTF 2026 with an exclusive Welcome Reception at Space Expo, the number 1 space museum in the Netherlands, located right next to ESA ESTEC. You will have the opportunity to network in a dynamic space-themed environment while exploring interactive exhibits and real spacecraft that highlight Europe's achievements in space exploration. Light refreshments will be served as participants reconnect with colleagues and meet new peers.

Please ensure that you are registered for the event as part of your conference registration.

Tuesday 21 April 2026 – 19:00 to 23:00 – Student Night - NH Leeuwenhorst

The Student Night at EFTF 2026 offers a unique opportunity to bring together students and experienced professionals from the Frequency and Time community. From the very first day of the conference, this informal and welcoming event is designed to foster connections, encourage dialogue across career stages, and help students begin building their professional network.

Please ensure that you are registered for the event as part of your conference registration.

Wednesday 22 April 2026 – 18:00 to 23:00 – Gala dinner - Louwman Museum

Join us for an unforgettable Gala Dinner at the Louwman Museum, home to one of the world's most extraordinary collections of historic automobiles. Enjoy an elegant evening surrounded by iconic vehicles and unique exhibits, creating a stylish and inspiring atmosphere to celebrate the EFTF community. This special night promises exceptional cuisine, engaging conversations, and a truly distinctive cultural experience.

Please ensure that you are registered for the event as part of your conference registration.

Additional Events and Visits

Tuesday 21 April - Women in Science Event – 17:30 to 18:30 – NH Leeuwenhorst Rotonde

The Women in Science event at EFTF 2026 provides a dedicated forum to highlight the role of women in the Frequency and Time community while fostering open dialogue on career development, visibility, and inclusion in science and engineering.

This year's session, "Engineering your career through effective communication," will be led by Dr. Yulia Akisheva and will focus on the critical role of communication in shaping scientific careers. Beyond technical excellence, the ability to clearly articulate ideas, position one's work, and engage in key professional conversations is essential to attract opportunities, build collaborations, and progress in one's career.

Friday 24 April - Satellite Workshop on Optical Clocks Based on Multiple Ions and VUV/XUV Transitions – 9:00 to 12:30

This satellite workshop will take place on Friday 24 April at ESA ESTEC, and will focus on recent advances in ion-based optical clocks, including multi-ion architectures and systems operating on VUV/XUV clock transitions such as highly charged ion and thorium nuclear clocks.

The program will highlight progress in precision spectroscopy, frequency metrology, and enabling technologies within the HIOC European Partnership on Metrology project. Designed to complement the main EFTF conference program, the workshop will offer dedicated presentations from consortium members and invited experts, with no overlap with EFTF technical sessions.

Please ensure that you have received a confirmation of your registration.

Friday 24 April – Tour to the Dutch National Metrology Institute (VSL) – 14:00 to 18:00

VSL manages and develops primary measurement standards and primary reference materials on behalf of the Dutch government. These measurement standards are the foundation for reliable measurements in science, industry, fair trade and other areas.

VSL also participates in research projects to develop newer and better measurement methods.

We make measurement results from companies, laboratories and institutes directly traceable to national and international standards. We also calibrate measuring instruments on behalf of customers, produce reference materials, organise interlaboratory comparisons and transfer our metrology knowledge by providing training and consultancy.

VSL is a globally recognised metrology institute. Our knowledge and services provide a major contribution to the reliability, quality and innovation of products and processes in business and society.

Registrations will be collected at the Registration Desk during the conference and are limited to 50 participants.

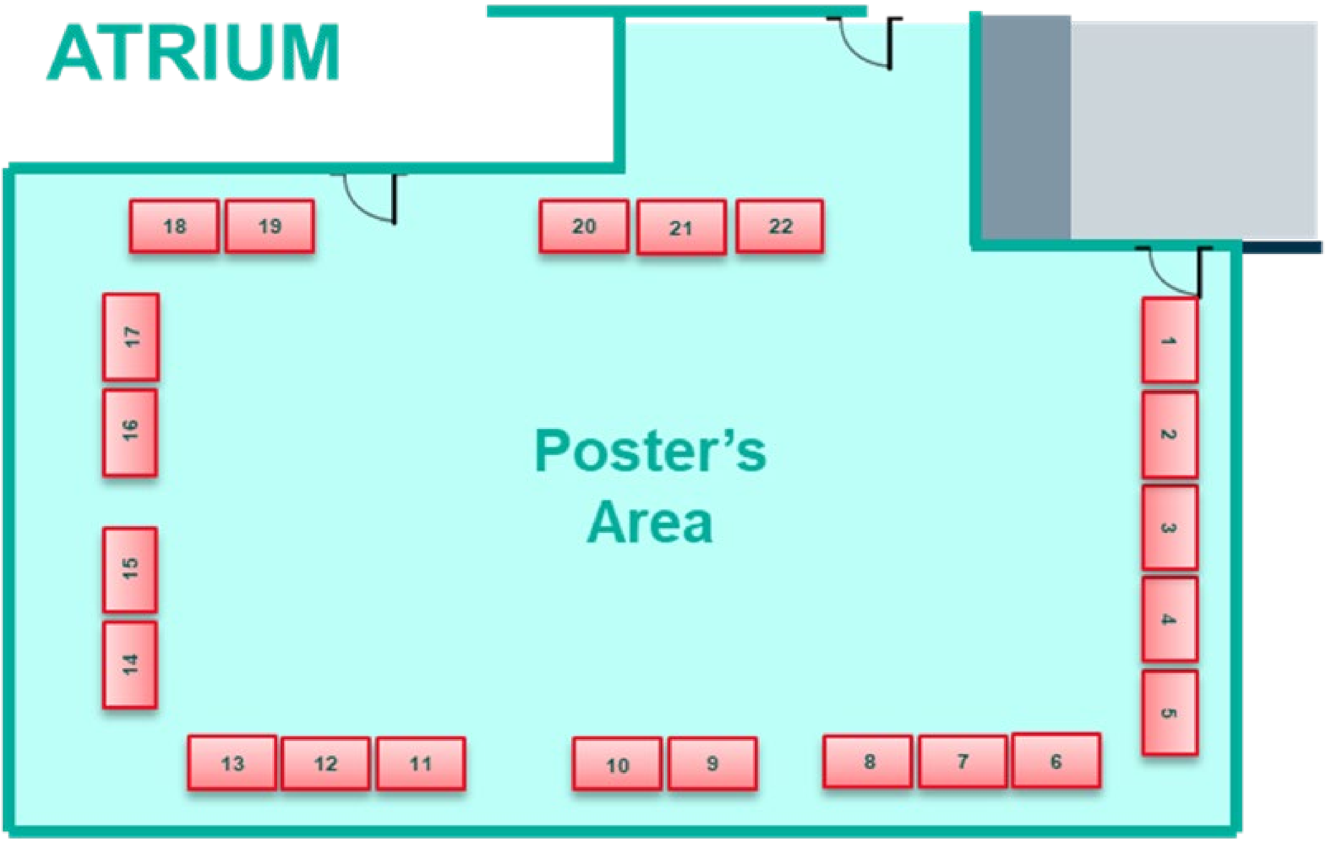
Friday 24 April – Tour to the ESA/ESTEC – Two rounds: 10:00–12:30/13:00 and 14:00–16:30/17:00

ESA has sites in several European countries, but the European Space Research and Technology Centre (ESTEC) in Noordwijk, the Netherlands, is the largest. ESTEC is our technical heart - the incubator of the European space effort - where most ESA projects are born and where they are guided through the various phases of development.

Please ensure you are registered for the tour. Limited to 40 participants per round.

Exhibitors

EFTF 2026 will welcome **22 industrial exhibitors** who will be showcasing their latest products and innovations throughout the 3 days of the conference. A dedicated exhibition area is set up in the Atrium.
Participants are warmly invited to explore, engage, and connect with them.
To help to find them, a map of the exhibition area is provided below.



1. Microchip Tech. *(premium sponsor)*
2. Cycle
3. Safran Trusted 4D
4. MUnique Technology
5. Piktime systems
6. FEMTO Engineering
7. TOPTICA Photonics
8. AQuRA
9. TimeTech *(premium sponsor)*
10. Oscilloquartz *(premium sponsor)*
11. Menlo Systems *(premium sponsor)*
12. Spherea Power & Instrumentation
13. Vexlum
14. Precise Time and Frequency
15. K2 Photonics
16. Spectradynamics
17. Vescent
18. Stable Laser Systems
19. Infleqtion *(premium sponsor)*
20. EXAIL *(premium sponsor)*
21. AXTAL *(premium sponsor)*
22. Silentsys *(premium sponsor)*

Special Session - Redefinition of the Second

Location: Rotonde
Date & Time: Thursday, 23 April (17:00 – 18:15)

The special session on the redefinition of the second offers a comprehensive overview of the scientific and institutional process leading toward a new definition of the SI unit of time. It offers an outline of the historical background that led to the current realisation based on the caesium atomic transition. The session will also review the international roadmaps developed over the past decade, illustrating how increasingly accurate and stable frequency standards are shaping the path toward a future redefinition.

In addition, the session will address the main technical and organisational challenges faced by the established international committees responsible for time and frequency metrology. These include ensuring global robustness and reliability of optical clock systems, establishing validated links for clock comparison at the required uncertainty levels, and achieving broad consensus within the international community. Particular attention will be given to the coordination efforts needed to meet the target of a redefinition of the second around 2030, ensuring continuity, transparency, and widespread accessibility of the new definition.

Noël Dimarcq – Président of the CCTF

Roadmap towards the redefinition of the SI second – Current status

Gaëtano Mileti – University of Neuchâtel

Historical Insights from the 1967 Redefinition of the Second

Davide Calonico – INRIM

Toward a Redefinition of the Second: Criteria

Sébastien Bize – LTE

Toward a Redefinition of the Second: Analysis of Options

Topic List

Group	Topic Name
1	Materials, Resonators, & Resonator Circuits
2	Oscillators, Synthesizers, Noise, & Circuit Techniques
3	Microwave Frequency Standards
4	Sensors & Transducers
5	Timekeeping, Time and Frequency Transfer, GNSS Applications
6	Optical Frequency Standards and Applications

Student Finalists

The following papers were selected as finalists by the EFTF 2026 Scientific Committee for the Student Poster Competition.

Location: Poster Area B12-B14
Date & Time: Tuesday April 21 (15:30 - 17:00)

Poster	Group	Title/Author
S1	2	**Temperature control optimization for Cryogenic Sapphire** *Mr. Mohamed-Yacine Hachani Engineer / PhD student Femto Engineering.*
S2	6	**Piezo-electrically tunable metrological Fabry-Perot cavity for a continuous superradiant laser** *Mr. Joshua Ruelle PhD student FEMTO-ST.*
S3	5	**High-Precision Free-Space Optical Frequency Dissemination Across a Sea Link** *Mr. Ming Li Student Shanghai Jiao Tong University.*
S4	6	**Measurement validation and cycle slip detection on a single optical frequency comb** *Mr. Alexander Burden Phd Student University Of Strathclyde*
S5	6	**Advancements in performance of the 171Yb+ ion optical clock at NPL** *Mr. Patrick Regan Scientist National Physical Laboratory.*
S6	3	**Evaluation of an Additive Manufactured Microwave Cavity for Compact Cold-Atom Clock Studies** *Miss Gabrijela Galic Phd Student University of Neuchatel.*
S7	5	**Novel Time and Frequency Transfer System Based on DORT Technology** *Mr. Adrian Romero Campelo Phd Student Hochschule München.*
S8	5	**Sub-Nanosecond Wireless Time Synchronization via OFDM Pilot-Based Fractional Timing Estimation** *Mr. Shirong Wei Postgraduate Student Beihang University.*
S9	2	**Hysteretic Reservoir Computing With Mems Oscillator Exhibiting Pinched-Hysteresis** *Mr. Fengdan Diao Ph.D Student University of York.*
S10	6	**Group Delay Measurement for Enhancing Spectral Hole Center Pointing and Reducing Laser Locking Frequency Drifts** *Mr. Axel Robbes Phd Student Observatoire De Paris Psl.*
S11	6	**Space qualification of a rubidium two-photon frequency reference** *Mr. Julien Kluge PhD Student Ferdinand-Braun-Institut gGmbh, Leibniz-Institut für Höchstfrequenztechnik.*
S12	2	**Compact dispersion-managed fiber laser based on a polarization-maintaining hybrid module** *Mr. Rongwei Zhu Student Shanghai Jiao Tong University.*
S13	6	**Locking a Chip-scale Laser to an Air-gap Optical Reference Cavity Based on an Optoelectronic Oscillator** *Dr. Zijie Zhou Shanghai Jiao Tong University.*
S14	3	**Frequency Detuning and Self-Recovery Stabilization Control System for the 87Rb Atomic *Fountain Clock*** *Mr. Fan Liu National Time Service Center, Chinese Academy of Sciences.*
S15	3	**Optical-injection based dual-frequency generator for compact CPT atomic clocks** *Mr. Tristan Barthelemy Thales Research & Technology.*

Poster	Group	Title/Author
S16	1	**Integrated Si3N4 high Q Microring Resonators Optoelectronic Oscillators** *Mr. Zeeshan Ahmed Marie Curie Phd Student III-V Lab.*
S17	2	**Ultra-low phase noise RF synthesis for Cs CPT atomic clock interrogation with an optoelectronic oscillator** *Mr. Jimmy Pennanech Phd Student Thales Las.*
S18	4	**Memristor-like Resonant MEMS Accelerometer** *Mr. Ryan Leatherbarrow Masters by Research Student University of York.*
S19	4	**Pinched Hysteresis within 1:1 Coupled MEMS Resonator** *Mr. Ang Li Beijing University of York.*
S20	1	**Novel Hammer-Shaped Electrode Design For Xbar (Hxbar) Q Enhancement** *Mr. Federico Peretti Phd Student EPFL.*
S21	6	**High-pulse-energy integrated mode-locked lasers enabling on-chip supercontinuum generation** *Mr. Zheru Qiu Doctoral Assistant EPFL/Swiss Federal Technology Institute of Lausanne.*
S22	5	**Sub-attosecond Optical Frequency Transfer via Photonic Integrated Interferometer** *Mr. Ziang Qiu PhD Student Shanghai Jiao Tong University.*
S23	6	**Impact of an optical redefinition of the SI second on the international time scales TAI and TT(BIPM)** *Ms. Roxanne Siadat Higher Scientist National Physical Laboratory (NPL).*
S24	3	**Development of an additively manufactured compact cold-atom fountain clock** *Mr. Samuel Smith PhD Student University of Strathclyde.*
S25	6	**Real-time measurement of the tidally induced geopotential changes via optical clocks** *Mr. Kilian Stahl PhD Student Physikalisch Technische Bundesanstalt.*
S26	6	**Transportable 171Yb Lattice Clock for Metrology and Geodesy** *Mr. Eric Swiler Graduate Student University Of Colorado Boulder.*
S27	3	**Progress on miniaturized laser-cooled 171Yb+ ion microwave clock** *Miss Ying Zheng Tsinghua University, Tsinghuayuan Road, Haidian District, Beijing, China Tsinghua University.*

Monday - April 20 - Tutorial Sessions

	Track 1 - High Bay	Track 2 - Auditorium
	Tutorials Registration & Welcome Coffee @ ESA ESTEC	
9:00 AM - 10:30 AM	Time Scales: how to practically realize UTC and UTC(k) Patrizia Tavella (BIPM, France)	Universal Optical Synthesis Marco Schioppo (NPL, UK)
10:30 AM - 11:00 AM	Coffee Break 1 @ Erasmus	
11:00 AM - 12:30 PM	GNSS applications in T&F Daniele Rovera (TFSol, France) / Pascale Defraigne (ROB, Belgium)	Chip scale devices for T&F John Kitching (NIST, USA)
12:30 PM - 2:00 PM	Lunch Break @ Erasmus	
2:00 PM - 3:30 PM	Fiber links and fiber sensing Cecilia Clivati (INRIM, Italy)	Optical Clocks Christian Lisdat (PTB, Germany)
3:30 PM - 4:00 PM	Coffee Break 2 @ Erasmus	
4:00 PM - 5:30 PM	Low Phase Noise Oscillators Jeremy Everard (York University, UK)	T&F metrology in Space: clocks and T&F transfer in GNSS Pierre Waller (ESA, The Netherlands)

Tuesday April 21 - Program Schedule

	Rotonde	B17/B19	C32
7:30 AM - 8:30 AM	Registration Day 1 @ NH Leeuwenhorst		
8:30 AM - 10:15 AM	Plenary session 1		
10:15 AM - 10:45 AM	Coffee Break 1		
10:45 AM - 12:15 PM	G5: Free space links & timescales Chair: Per Olof Hedekvist	G6: Ion optical clocks Chair: Rachel Godun	G1: Materials and resonators Chair: Marie Bousquet
12:15 PM - 1:15 PM	Lunch Day 1		
1:30 PM - 3:00 PM	G5: TFT in optical fibers 1 Chair: Jochen Kronjaeger	G6: Advanced optical clocks Chair: Simon Stellmer	G3: Frontier microwave-clock topics Chair: Mohsin Haji
3:00 PM - 3:30 PM	Coffee Break 2		
3:30 PM - 5:00 PM	Poster competition Poster session 1		
5:30 PM - 6:30 PM	Women in Science Event @ NH Leeuwenhorst		
7:00 PM - 11:00 PM	Student Night @ NH Leeuwenhorst		

G5: Free space links & timescales

Chair: Per Olof Hedekvist

Paper Number	Presenting Author Names	Organization	Paper Title
100	*Dr. Emily Caldwell*	*NIST*	*Free-space time transfer between Yb Lattice Clocks on Mt. Bluesky (elevation 4300 m) and NIST (elevation 1650 m)*
248	Dr Sabrina Slimani	Icrar	Free-space optical-frequency comparison between moving optical clocks
150	Dr. Juhyun Lee	Korea Research Institute of Standards and Science(KRISS)	SDR Design for Signal Processing and Code Phase Measurement of TWSTFT Signals
6	Dr. Daniele Monahan	The Aerospace Corporation	Realization of a Kuramoto Timescale

G6: Ion optical clocks

Chair: Rachel Godun

Paper Number	Presenting Author Names	Organization	Paper Title
341	*Dr. Mason Marshall*	*National Institute Of Standards And Technology*	*The NIST Aluminum Ion Clock*
305	Ms. Melina Filzinger	Physikalisch-Technische Bundesanstalt (PTB)	A multi-ion optical clock with 5.3×10^-19 systematic uncertainty
39	Dr. Claude Marceau	National Research Council Canada	Absolute frequency measurement of 88Sr+ at the 10-16 level
162	Mr. Michael Lee	Centre For Quantum Technologies, National University Of Singapore	Comparison of 176Lu+ optical frequency references having 1x10^-19 systematic uncertainty with 5.3x10^-19 precision

G1: Materials and resonators

Chair: Marie Bousquet

Paper Number	Presenting Author Names	Organization	Paper Title
344	*Dr. Tony Makdissy*	*Soitec*	*L-band Resonant Gap Surface Acoustic Wave Filter with Reconfigurable Potentialities for Space Applications*
93	Mr. Federico Peretti	EPFL	Novel Hammer-Shaped Electrode Design For Xbar (Hxbar) Q Enhancement
37	Mr. Florian Hartmann	EPFL NEMS	Innovative TCF Compensation Architecture for Bulk Acoustic Resonators
55	Mr. Zeeshan Ahmed	III-V Lab	Integrated Si3N4 high Q Microring Resonators

G5: TFT in optical fibers 1

Chair: Jochen Kronjaeger

Paper Number	Presenting Author Names	Organization	Paper Title
213	*Dr. Michael Kriele*	*University Of Western Australia*	*The SKA-MID Frequency Distribution System - Update*
81	Mr Mathieu Collombon	Aix-Marseille Université - CNRS - Laboratoire PIIM	Characterization of the Refimeve metrological signal 1000km from the source
105	Mr. Ziang Qiu	Shanghai Jiao Tong University	Sub-attosecond Optical Frequency Transfer via Photonic Integrated Interferometer
231	Dr. Nils Nemitz	NICT	Establishing infrastructure for NICT's optical frequency distribution

G6: Advanced optical clocks

Chair: Simon Stellmer

Paper Number	Presenting Author Names	Organization	Paper Title
16	*Prof. Shiqian Ding*	*Tsinghua University*	*A continuous-wave 148.4 nm laser for a Th-229 nuclear clock*
335	Dr. Ekkehard Peik	PTB	Continuous-wave laser source at the 148 nm nuclear transition of Th-229
217	Dr. Jialiang Yu	Physikalisch-technische Bundesanstalt	Multi-ion optical clock with 173Yb+
289	Dr. Harikesh Ranganath	National Institute of Standards and Technology, Boulder	Lattice light-shift model errors in optical lattice clocks

G3: Frontier microwave-clock topics

Chair: Mohsin Haji

Paper Number	Presenting Author Names	Organization	Paper Title
184	*Dr. Zihan Xu*	*National Time Service Center*	*Fourier-Embedded Neural Networks for Clock Transition Spectroscopy Reconstruction*
26	Miss Ying Zheng	Tsinghua University	Progress on miniaturized laser-cooled 171Yb+ ion microwave clock
21	Dr. Sean Dyer	University Of Strathclyde	Improving the short-term stability of a coherent population trapping clock via a stimulated Raman transition
90	Mr. Vladimir Dolgovskiy	Oscilloquartz	Optically-pumped cesium beam clock with reduced cost by means of a cavity-integrated vacuum enclosure

	Rotonde	B17/B19	C32
8:00 AM - 8:30 AM	Registration Day 2 @ NH Leeuwenhorst		
8:30 AM - 10:15 AM	Plenary session 2		
10:15 AM - 10:45 AM	Coffee Break 3		
10:45 AM - 12:15 PM	G5: Optical TFT in space Chair: Anne Amy Klein	G6: Optical frequency combs Chair: Erik Benkler	G3: Cold-atom deployable clocks Chair: Daniele Monahan
12:15 PM - 1:15 PM	Lunch Day 2		
1:30 PM - 3:00 PM	G5: Microwave TFT in space Chair: Sinda Mejri	G6: Clock comparisons Chair: Michał Zawada	G2: Oscillators, synthesis, and noise Chair: Enrico Rubiola
3:00 PM - 3:30 PM	Coffee Break 4		
3:30 PM - 5:00 PM	G5: Timescales Chair: Pascale Defraigne	G6: Deployable optical clocks Chair: Takumi Kobayashi	G4: Micro and nano resonant sensors Chair: Michael Schneider
5:00 PM - 6:00 PM	Logistics Break		
6:00 PM - 6:30 PM	Bus Transfer to Louwman Museum		
6:00 PM - 11:00 PM	Gala Dinner @ Louwman Museum		

G5: Optical TFT in space

Chair: Anne Amy Klein

Paper Number	Presenting Author Names	Organization	Paper Title
169	*Eng. Ning Yu*	*National Time Service Center*	*Progress on the Space-to-Ground Laser Time-and-Frequency Transfer Link Experiment for the China Space Station*
175	Dr. Anja Schlicht	TU Munich	ELT: An optical time transfer method using laser pulses
116	Dr. Dominik Bourgund	Deutsches Zentrum für Luft- und Raumfahrt e. V., Institut für Kommunikation und Navigation	Optical frequency transfer in the presence of large Doppler shifts and rates for optical satellite links
46	Mr. Shawn Mcsorley	International Centre For Radio Astronomy Research	A Doppler Simulator for Future Ground-to-Space Time and Frequency Transfer

G6: Optical frequency combs

Chair: Erik Benkler

Paper Number	Presenting Author Names	Organization	Paper Title
96	*Franklyn Quinlan*	*NIST*	*Low Noise Photonic Microwave Generation with Free-running Frequency Combs and Feedforward Correction*
202	Mr. Zheru Qiu	EPFL/Swiss Federal Technology Institute of Lausanne	High-pulse-energy integrated mode-locked lasers enabling on-chip supercontinuum generation
91	Eng. Niccolò Salvatore Barberio	Politecnico Di Milano	10-GHz broadband low-noise Er-doped solid-state optical frequency comb
195	Dr. Matthias Lezius	Menlo Systems Gmbh	Frequency-Combs for Optical Clocks in Space

G3: Cold-atom deployable clocks

Chair: Daniele Monahan

Paper Number	Presenting Author Names	Organization	Paper Title
256	*Dr. François Xavier Esnault*	*CNES Centre National d'Études Spatiales*	*The Operation of the Primary Frequency Standard, PHARAO, in Space*
149	Dr. Akifumi Takamizawa	National Metrology Institute of Japan, AIST	Balanced Grating Magneto-Optical Trap for a Miniature Cold Cesium Atomic Clock
221	Mr. Samuel Smith	University of Strathclyde	Development of an additively manufactured compact cold-atom fountain clock
20	Mr. BRUNO PELLE	Exail - Quantum Systems	Consolidated accuracy budget of a cold-atom-based commercial microwave clock reaching 2×10-14

G5: Microwave TFT in space

Chair: Sinda Mejri

Paper Number	Presenting Author Names	Organization	Paper Title
283	*Dr. Marc Lilley*	*LTE, Observatoire De Paris*	*ACES Microwave Link in-orbit performance characterization*
295	Eng. Carsten Rieck	RISE Research Institutes of Sweden	Frequency and Time Transfer with ESA's Genesis Satellite
339	Mr. Wolfgang Schäfer	TimeTech GmbH	ACES Microwave Link Architecture
139	Mrs. Pascale Flagel	European Space Agency	Galileo Space Clocks Research and Development Programme

G6: Clock comparisons

Chair: Michał Zawada

Paper Number	Presenting Author Names	Organization	Paper Title
219	*Marco Pizzocaro*	*Inrim*	*International Optical Clock Comparisons Using the European Optical Fibre Network*
89	Dr. Rachel Godun	National Physical Laboratory (NPL)	Frequency ratios with NPL 171Yb+ optical frequency standard
189	Dr. Irene Goti	INRIM	Yb/Sr optical frequency ratio with a transportable clock
95	Dr. THOMAS LAUPRETRE	Laboratoire Temps Espace	First optical frequency ratio measurement with the forbidden 1S0-3P0 clock transition in bosonic 198Hg

G2: Oscillators, synthesis, and noise

Chair: Enrico Rubiola

Paper Number	Presenting Author Names	Organization	Paper Title
365	*Dr. Vincent Giordano*	*Cnrs Femto-st Institute*	*Cryogenic Sapphire Oscillators: From Concept to State-of-the-Art Microwave References and Commercial Products*
51	Dr. Enrico Lia	Esa-estec	Millimeter-wave Voltage Controlled Oscillators based on electronic bandgap material resonators for application in space
28	Dr. Florian Ramian	Rohde & Schwarz	Advances in Cross Correlation in Signal- and Spectrum Analysis
83	Jimmy Pennanech	Thales Las	Ultra-low phase noise RF synthesis for Cs CPT atomic clock interrogation with an optoelectronic oscillator

G5: Timescales

Chair: Pascale Defraigne

Paper Number	Presenting Author Names	Organization	Paper Title
220	*Dr. Patrizia Tavella*	*BIPM*	*Progressing towards a Continuous UTC*
12	Dr. Bin Jian	National Research Council Canada	Timescale Accuracy When Steered Using Different Frequency Prediction Methods
73	Mr. Christian Trainotti	German Aerospace Center	Onboard ensemble timescale realization for synchronization of future G2G-like constellations
148	Dr. Gianna Panfilo	Bipm	TT(BIPM): its realization and use as a long-term reference Timescale

G6: Deployable optical clocks

Chair: Takumi Kobayashi

Paper Number	Presenting Author Names	Organization	Paper Title
364	*Prof. Andre Luiten*	*Adelaide University*	*Optical frequency standards on the move: land, sea, and space*
246	Mr. Eric Swiler	University Of Colorado Boulder	Transportable 171Yb Lattice Clock for Metrology and Geodesy
257	Mr. Kilian Stahl	Physikalisch Technische Bundesanstalt	Real-time measurement of the tidally induced geopotential changes via optical clocks
86	Dr. Frederik Kuschewski	German Aerospace Center	Frequency Reproducibility of Hyperfine Transitions in Iodine Vapor Cells for Optical Clock Technology

G4: Micro and nano resonant sensors

Chair: Michael Schneider

Paper Number	Presenting Author Names	Organization	Paper Title
350	*Prof. Peter G. Steeneken*	*Delft University Of Technology*	*Resonant Sensors from 2D Materials*
308	Mr. Ang Li	University of York	Pinched Hysteresis within 1:1 Coupled MEMS Resonator
22	Professeur. Jerome Juillard	CentraleSupelec - GEEPS	Design of a MEMS-based photo-acoustic pressure sensor – Capacitive approach
237	Mr. Ryan Leatherbarrow	University of York	Memristor-like Resonant MEMS Accelerometer

Thursday April 23 - Program Schedule

	Rotonde	B17/B19	C32
8:15 AM - 8:45 AM	Registration Day 3 @ NH Leeuwenhorst		
8:45 AM - 10:15 AM	G5: Satellite based TFT Chair: Jerome Delporte	G6: Commercial optical clocks Chair: Yige Lin	G6+G2: Ultrastable lasers Chair: Bess Fang
10:15 AM - 10:45 AM	Coffee Break 5		
10:45 AM - 12:15 PM	G5: TFT in optical fibers 2 Chair: Carsten Rieck	G6: Optical clocks metrology Chair: Clara Zyskind	G2: Phase-frequency comparisons and analysis Chair: Andrew Novick
12:15 PM - 1:15 PM	Lunch Day 3		
1:30 PM - 3:00 PM	G5: White rabbit Chair: Ilaria Sesia	G5+G6: Redefinition of the second Chair: Jonathan Gillot	G3: Vapor-cell deployable clocks Chair: Salvatore Micalizio
3:00 PM - 3:30 PM	Coffee Break 6		
3:30 PM - 5:00 PM	Poster session 2		
5:00 PM - 6:15 PM	Special session: redefinition of the second		
6:15 PM - 6:30 PM	Closing Session		

G5: Satellite based TFT

Chair: Jerome Delporte

Paper Number	Presenting Author Names	Organization	Paper Title
230	*Mr. Tung Thanh Thai*	*INRiM*	*2025 Carrier-phase Two-Way Satellite Time and Frequency Transfer measurements in Europe*
281	Dr. Elisa Pinat	Royal Observatory Of Belgium	Monitoring of Galileo Broadcast Group Delays
186	Dr. Michael Plumaris	European Space Agency	Passive TWSTFT: A cost-effective alternative for robust UTC(k) dissemination
79	Dr Jiang Guo	BIPM	Multi-Constellation IPPP Link for UTC

G6: Commercial optical clocks

Chair: Yige Lin

Paper Number	Presenting Author Names	Organization	Paper Title
366	*Mr. Takashi Muramatsu*	*Shimadzu Corporation*	*A Commercial Strontium Optical Lattice Clock with 250 liters*
310	Dr. Pierre Thoumany	TOPTICA Photonics SE	A commercial single-ion optical frequency standard with a systematic uncertainty below 2E-17
198	Dr. Jonathan Roslund	Vector Atomic	Development of a 5-liter iodine optical atomic clock
324	Saaswath Jeyalathaa Karthikeyan	Physikalisch-Technische Bundesanstalt	Transportable optical clock for remote comparisons and contributions to timescales

G6+G2: Ultrastable lasers

Chair: Bess Fang

Paper Number	Presenting Author Names	Organization	Paper Title
94	*Dr. Marco Schioppo*	*National Physical Laboratory (NPL)*	*Laser fractional frequency instability below 6×10^-17 with room temperature optical reference cavities*
153	Dr. Chun Yu Ma	PTB Braunschweig	Room-temperature ultra-stable cavity with crystalline coatings enabling fractional instability near 4 × 10-17
154	Mr Pierre Roset	Femto-st / Umlp	Toward a Silicon Fabry–Perot Cavity with Sub-10^{-17} Stability in a Dilution Cryostat
84	Mr. Jimmy Pennanech	Thales Las	Optoelectronic oscillator based on self-injection locking on a high quality factor fiber Fabry-Perot resonator

G5: TFT in optical fibers 2

Chair: Carsten Rieck

Paper Number	Presenting Author Names	Organization	Paper Title
131	*Dr. Charles McLemore*	*National Institute Of Standards And Technology*	*A new limit on real-time noise-cancelled fiber links*
161	Dr. Xiao Xiang	National Time Service Center, CAS	Sub-picosecond Quantum Time Synchronization Over 120-km Fiber for Scalable Quantum Networks
236	Dr. Cecilia Clivati	INRIM	Coherent Laser Interferometry for Distributed Sensing and Event Localization
126	Dr. Holly Leopardi	University of Maryland, Baltimore County	Alternative approach to time delay interferometry with optical frequency comb

G6: Optical clocks metrology

Chair: Clara Zyskind

Paper Number	Presenting Author Names	Organization	Paper Title
280	*Dr. Thomas Lindvall*	*VTT, National Metrology Institute VTT MIKES*	*High-Uptime 88Sr+ Optical Clock with 7.9×10−19 Uncertainty*
71	Dr. Daniela Weston	National Physical Laboratory	A paper realisation of optically steered time scales at NPL
251	Mr. Jérôme Lodewyck	Lte/lne-op, Obseravatoire De Paris	High up-time calibrations of TAI with a Sr optical lattice clock
294	Dr. Zixiao Ma	Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences	Evaluation of Light Shift and AOM Chirp Effect in a Ca+ Optical Clock

G2: Phase-frequency comparisons and analysis

Chair: Andrew Novick

Paper Number	Presenting Author Names	Organization	Paper Title
155	*Dr. Manuel Martin-Neira*	*ESA*	*Upper Side Band Syntonization and Synchronization concept of a set of N Satellites*
242	Prof. Enrico Rubiola	Institut FEMTO-ST	Oscillator ensemble for phase noise comparison
286	Mr. Omid Abed	Phy-si-ka-lisch-tech-ni-sche Bun-des-an-stalt (PTB)	Establishment of Phase Noise Traceability to SI Units in PTB
17	Dr. Ivo Puncochar	Západočeská univerzita v Plzni	Identification of Clock Ensemble Noise Parameters Using Differential Measurement Analysis

G5: White rabbit

Chair: Ilaria Sesia

Paper Number	Presenting Author Names	Organization	Paper Title
330	*Mr. Paul Boven*	*JIVE*	*White Rabbit in Radio Interferometry*
187	Dr. Jeroen Koelemeij	Vrije Universiteit Amsterdam	Picosecond-Range White Rabbit Digital Time Scale
114	Dr. Jochen Kronjäger	Physikalisch-Technische Bundesanstalt (PTB)	Chromatic Dispersion-Free Approach for High-Accuracy Time Synchronization in White Rabbit Networks
215	Dr. Martin Langer	Physikalisch-Technische Bundesanstalt (PTB)	Cryptographically Secured High-Performance Time Synchronization for Long-Distance White Rabbit Links

G5+G6: Redefinition of the second

Chair: Jonathan Gillot

Paper Number	Presenting Author Names	Organization	Paper Title
87	*Dr. Helen Margolis*	*National Physical Laboratory (NPL)*	*2025 update to the CIPM list "Recommended values of standard frequencies"*
264	Dr. Nils Nemitz	NICT	Visualizing the Ensemble Second
292	Dr. Ion Mihailescu	University of Neuchâtel	The most suitable standard and the right moment for a redefinition: a historical perspective
142	Ms. Roxanne Siadat	National Physical Laboratory (NPL)	Impact of an optical redefinition of the SI second on the international time scales TAI and TT(BIPM)

G3: Vapor-cell deployable clocks

Chair: Salvatore Micalizio

Paper Number	Presenting Author Names	Organization	Paper Title
7	*Dr. James Camparo*	*The Aerospace Corporation*	*LaLI-POP Frequency Stability and Light Shift: Phase-1 Testbed*
302	Dr. Annamaria Campa	Leonardo S.p.a.	Advancing Rubidium Pulsed Optical Pumping (Rb POP) atomic clock for Galileo experimental flight
218	Mr. Florian Gruet	Laboratoire Temps-fréquence, Université De Neuchâtel	Pulsed Frequency-Doubled Laser System for Rb Atomic Frequency Standards
311	Dr. Juliette Breurec	Thales TRT	Progress Towards the Development of a Compact and High-Performance Cs CPT Clock

Poster session 1 – Tuesday April 21 - 15:30 – 17 :00 • Poster areas – Atrium & B9

Poster	Paper	Presenting Author Names	Organization	Paper Title
A1	13	Mr. Shinn Yan Lin	Telecommunication Laboratories	Long-Term Time Transfer Performance Evaluation of a Low-Cost GNSS Receiver Module
A2	315	Mr Meir Alon	Tel Aviv University	Frequency Dissemination Using Brillouin Amplification
A3	27	Mr. Vimalkumar Chawda	Uni Bremen	Smart Sensor Fusion for Robust Initialisation and Accurate Trajectory Estimation
A4	30	Mr. Juan Manuel Cruz Blazquez	Safran Electronics & Defense Spain, S.L.U.	White Rabbit-based distributed clock ensemble for increased timing resilience
A5	34	Dr. Rabia Ince	National Physical Lab, Uk	Integrating Artificial Intelligence into Atomic Clock Systems
A6	35	Wu Dan	National Time Service Center Chinese Academy Of Sciences	An Improved Algorithm for Sub-LOF Anomaly Detection Based on Bayesian Optimization
A7	123	Dr. Zongyuan Li	National Time Service Center, Chinese Academy Of Sciences	Adaptive Atomic Clock Difference Prediction Algorithm Based on ARIMA-BiLSTM Model
A8	80	Dr. Zongyuan Li	National Time Service Center, Chinese Academy of Sciences	Weak Frequency Jump Detection in Atomic Clocks Based on a Dual-Filter Difference Algorithm
A9	52	Dr. Peihao Cheng	Beijing Institute Of Radio Metrology And Measurement	Design of Optical Costas Phase Lock Loop in Homodyne Coherent Optical Receiver
A10	58	Mr. Yuchen Wang	National Time Service Center	Methods and Analysis of Inter-System Time Offset Prediction for GNSS
A11	268	Eng Waleed Alharbi	Saudi Standards, Metrology And Quality O	Comparison and Time Domain Evaluation of two GNSS TTS-4 Receiver Systems Referenced to a Common Cs Clock
A12	65	Eng. Waleed Alharbi	Saudi Standards Metrology & Quality Organization (saso-nmcc)	Comparison of UTC Time Scales of SASO, UME, UzNIM, NIS, AzMI, EMI Using the GNSS Common-View Method
A13	188	Mr. Leo Sol	Cnes	Coordination of Clock Steering and Timescale Generation over a Swarm of Satellites
A14	102	Miss Guoying Wu	Casic	Research on a High-Precision Microwave Two-Way Time Transfer Method Based on Noncommensurate Sampling
A15	120	Dr. Hanxu Wu	Beijing Institute Of Radio Metrology And Measurement	Three-Month-Long Parallel Distribution of UTC(NIM) Time Scale and Strontium Optical Lattice Frequency Standard at NIM over a Single Fiber Communication Channel
A16	138	Miss Linlin Li	Chengdu University Of Technology	Temperature-insensitive Two-way Phase Stabilized Optical Frequency Transfer
A17	163	Ms. Shiguang Wang	Tsinghua University	Replicated Clock on an Unmanned Aerial Vehicle with Picosecond-level Precision in Three-dimensional Motion
A18	159	Dr. Xinxing Guo	Chinese Academy of Sciences	A High-Precision and Automated Testbed for Fiber-Optic Time Transfer Equipment Calibration
A19	173	Dr. Cecilia Clivati	INRIM	SENSEI project: sensing on the EU metrology fiber network
A20	196	Dr. Yanming Guo	National Time Service Center, Chinese Academy Of Sciences	Unified Error Analysis for Microwave Satellite–Ground Time Transfer: Kinematic, Relativistic Periodic, Atmospheric, and Hardware Delay Effects
A21	285	Dr. BIPLAB DUTTA	Laboratoire De Physique Des Lasers	Upgrade of REFIMEVE network for low-noise long-distance frequency transfer
A22	296	Dr Edward Gluszak	University Of Western Australia	An interim active fibre-stabilisation and frequency distribution system for SKA-MID commissioning
A23	232	Mr. Christopher Dennis	National Institute Of Standards And Technology	Frequency Transfer Over 80km of Fiber Supporting the NIST-to-Mt. Bluesky Clock Comparison
A24	258	Dr. Wei Huang	National Physical Laboratory	Fibre-Optic Time and Optical Frequency Dissemination in a Single DWDM Channel using the Spread Spectrum Technique
A25	293	Dr. Hao Gao	Beijing University of Posts and Telecommunications	Optical Pointing Compensation under Atmospheric Turbulence for Free-Space Frequency Transfer
A26	124	Hao Gao	North China Electric Power University	Stable RF Transmission Based on Optical Frequency Shift
A27	275	Dr. Hao Gao	Beijing University of Posts and Telecommunications	Stable Frequency and 100G/s data transmission through ur-ban underground optical fiber
A28	287	Dr. Carlo Page	Xairos UK	Enabling Future Distributed Sensing Applications through Quantum Time Transfer

Poster	Paper	Presenting Author Names	Organization	Paper Title
A29	328	Mr. David Verner	Cesnet	Towards Large Scale White Rabbit Network
A30	113	Dr. Jochen Kronjäger	Physikalisch-technische Bundesanstalt	White Rabbit Time and Frequency Distribution with Picosecond Accuracy in a Deployed Quantum Testbed
A31	119	Mr. Weinan Zhao	China Jiliang University	Doppler Simulator Technology for Optical Time-Frequency Transfer
A32	314	Dr. Harald Hauglin	Justervesenet - Norwegian Metrology Service	Setup and performance of resilient reference timing services at Jammertest 2025
A33	320	Dr. Harald Hauglin	Justervesenet - Norwegian Metrology Service	Time and Frequency Activities at Justervesenet
A34	332	Ms. Yan Xie	VSL National Metrology Institute of the Netherlands	A unified PTP link calibration model under IEEE Standard 1588-2019
A35	334	Mr. Paweł Zienkiewicz	Creotech Instruments S.A.	Building blocks for mmWave 5G and 6G Infrastructure time and frequency synchronization
A36	331	Dr. Neelam Neelam	Laboratoire Temps Espace, Observatoire De Paris	Precise Time Calibration and Deployments of White Rabbit Switches for T-REFIMEVE
A37	333	Dr. Dong Zhang	Beihang University	Refining the reference time of IGS real-time products for PPP one-way timing
A38	15	Dr. Stefano Barsotti	Intecs Spa	GIASONE-2: A Scalable and Authenticated Infrastructure for Advanced GNSS Signal Integrity Monitoring
A39	8	Dr. Israel Rebolledo-Salgado	RISE Research Institutes Of Sweden	Frequency characterization of chip-scale frequency combs
A40	107	Dr. Mayuri Nakagawa	NTT Inc.	Simple and Highly Precise Frequency Replication from Mode-Locked Frequency Comb to Electro-Optic Comb
A41	179	Dr. Hyun Gyung Lee	Korea Research Institute Of Standards And Science	A Compact Strontium Atomic Beam Source Enabled by a Two-Dimensional Grating MOT
A42	157	Mr. Hangzhe Lyu	Peking University	Compact, digital controlled optical atomic clock
A43	134	Ms. Luz Martinez	Vector Atomic	Trapping Laser System for Deployed Strontium Clock
A44	63	Mr. Jesús Romero Gonzalez	ROA	Recent Developments in Optical Measurement at ROA
A45	197	Ms. Hannah Tomio	Massachusetts Institute Of Technology	Characterization and Performance of an Optical Frequency Comb for Space
A46	59	Mr. Joshua Klose	Physikalisch-technische Bundesanstalt (PTB)	Progress of PTB's strontium optical lattice clock Sr3
A47	56	Mr. Chen Feng	Peking University	A high-performance optical clock stabilized on 5S-5D two photon transition of rubidium
A48	152	Dr. Xinyi Chen	Beijing Institute Of Radio Metrology And Measurement	Ultrahigh-stability Microwave Generated via Optical Frequency Division of an Ultrastable Laser
A49	271	Dr. Xinyi Chen	Beijing Institute Of Radio Metrology And Measurement	Rapid Measurement of the Zero-Expansion Temperature Point (T_0) in a 30cm-Long Optical Reference Cavity via Single Temperature Scan
A50	252	Pierre Eberschweiler	CNRS	AQuRA, a prototype industrial transportable optical clock
A51	70	Miss Eilidh Maclennan	University Of Strathclyde	Construction of a Compact Two Photon Optical Clock Using Micro-machined Vapour Cells
A52	97	Dr. Thomas Easton	NPL	High Availability Yb Optical Lattice Clocks at NPL
A53	98	Dr. Andrea Pertoldi	Menhir Photonics AG	Ruggedized and Hermetic Laser Module for Space-Qualified Ultra-Low-Noise GHz-Repetition-Rate Frequency Combs
A54	101	Dr. Shaoyang Dai	National Institute of Metrology, China	The preliminary evaluation of the NIM-Yb1 Ion Optical Clock
A55	128	Dr. Steven Johnson	University of Strathclyde	A Rubidium 2-photon Frequency Reference using Fibre Components
A56	288	Dr. Benjamin Rauf	Menlo Systems GmbH	Mid-10-15 Stability Optical Cavity in a Sub-Liter Passive Vacuum Chamber
A57	122	Dr. Takumi Kobayashi	National Metrology Institute of Japan	Status report of the activities in the OptAsia collaboration
A58	130	Mr. Pierre Roset	Femto-st / Umlp	Low noise distribution, transfer and measurement system for optical ultra stable signal.
A59	147	Mr. Michele Gozzelino	INRIM	Rb microcells production for chipscale optical clocks

Poster	Paper	Presenting Author Names	Organization	Paper Title
A60	250	Mr. Michael Lee	Centre For Quantum Technologies, National University Of Singapore	Precision measurement of the 176Lu+ 3D1 unperturbed microwave clock transition frequencies
A61	160	Dr. Jonas Keller	Physikalisch-Technische Bundesanstalt	Scaling high-accuracy Coulomb crystal clock operation to tens of ions
A62	165	Dr. Igor Broeckel	DLR-SI	On the correction of differential light shifts in an optical dipole trap
A63	168	Dr. Clara Zyskind	Physikalisch-Technische Bundesanstalt	Yb+ isotopes spectroscopy and tests of fundamental physics
A64	171	Dr. Seji Kang	Korea Research Institute Of Standards And Science	Laser frequency reference using a microfabricated vapor cell with formable film getter for vacuum maintenance
A65	178	Dr. Anand Prakash	Leibniz Universität Hannover	A 3D diamond ion trap with integrated optics for frequency metrology
A66	193	Dr. Thomas Puppe	Toptica Photonics SE	Ultra-low phase noise from X- to the terahertz-band via comb-based frequency division and synthesis
A67	226	Dr. Chetan Vishwakarma	PTB Braunschweig	Interspecies clock comparisons and chronometric geodesy using a transportable optical lattice clock
A68	223	Dr. Minh Nhut Ngo	Université Sorbonne Paris Nord	SI-traceable molecular frequency measurements around 30 THz within sub-kHz uncertainty
A69	216	Dr. Zhiyu Ma	Huazhong University of Science and Technology	Research Progress of Optical Frequency Standards at Huazhong University of Science and Technology
A70	336	Ms. Courtney Reid	University Of Birmingham	Characterisation of a Lab-based Strontium Optical Lattice Clock
A71	229	Mr. Alan Boudrias	FEMTO-ST	Characterization of a doped-silicon surface-electrodes trap for optical frequency metrology
A72	235	Ms. Anne-katrin Landa	LTE, Observatoire de Paris	Construction of an 171Yb Optical Lattice Clock for Geodetic Exploration
B1	18	Dr. ohammad Zaid	University Of Cambridge	Piezoelectric MEMS-enabled acoustic phonon pulses for high-speed modulation in terahertz quantum cascade lasers: Direct comparison of ZnO-based SAWs and BAWs
B2	85	Dr. Kaoutar Zeljami	Alter Technology TüV Nord	Space Qualification of SAW Filters Based on POI Technology
B3	68	Dr. Sebastian Häfner	Technische Universität Braunschweig	Progress in the Development of Low-Loss Nanostructured Mirrors for Ultra-Stable Resonators
B4	244	Mr. Muhammad Awais Maqbool	Queen's University Belfast	Coupled Quartz Crystal Resonators with Active Thermal Stabilization for Achieving a Higher Frequency Stability
B5	33	Ms. Enise Kartal	Delft University Of Technology	Graphene Parametric Oscillator
B6	42	Mr. Junchao Wang	Peking University	A Neural Compensator for Fast Recovery from Frequency Jumps in Temperature-Compensated Crystal Oscillators
B7	298	Mr. Jiayue Shen	Peking University	Comparative Study of SESAM-Mode-Locked All-Fiber Erbium Oscillators: Cavity-Dependent Stability and Soliton Dynamics
B8	76	Mr.先生 Meng Shi	Peking University	Optimizing Long-Term f_rep Stability of a Mode-Locked Laser via Simulation-Based Genetic Algorithm
B9	129	Prof Enrico Rubiola	Institut FEMTO-ST	Phase noise measurement of optical amplifiers
B10	225	Mr Francesco Rocco Nardelli	Politecnico Di Bari	Preliminary Characterization of a Thermo-Optically Tunable L-Band OEO based on a Silicon Nitride Ring Resonator
B11	272	Mr Fan Liu	National Time Service Center, Chinese Academy Of Sciences	Design and development of the detection zone and state-selection cavity with coordinated optimization for a time-keep-ing 87Rb fountain clock
B12	66	Dr. Meung Ho Seo	Korea Research Institute of Standards and Science	Progress Report on the Optical System for the Rubidium Fountain Clock at KRISS
B13	67	Prof. Xiaochi Liu	Innovation Academy for Precision Measurement Science and Technology	Cold atoms coherent population trapping clock based on miniature magneto-optical trap
B14	136	Gabriel Faure	CNRS / FEMTO-ST	Microfabricated vapor cells with tunable buffer gas mix-tures using laser-actuated break-seal reservoirs
B15	156	Dr. Youngho Park	Korea Research Institute of Standards and Science	Testing Prototype Cavity with Minimized Temperature Coefficient of Resonance Frequency for Rb Fountain Clock
B16	214	Dr. Gilles Cibiel	Safran Timing Technologies	European ultra-stable atomic clocks Ground Active Hydrogen Maser: Status and progress report

Poster	Paper	Presenting Author Names	Organization	Paper Title
B17	247	Dr. Hongli Liu	Huazhong University of Science and Technology	The improvement of the frequency stability of an atomic ce-sium fountain at HUST
B18	253	Dr. Roman Blum	Safran Timing Technologies	Miniature and chip-scale rubidium microwave atomic clocks: Industry trends and roadmap at Safran Timing Technologies
B19	31	Mr. Will Emanuel	Microchip Technology Inc.	Low SWaP Embedded Atomic Clocks for Space
B20	238	Dr. Erik Benkler	PTB	Software Defined Radio Devices for Optical Frequency Metrology
B21	245	Murray Barrett	Center For Quantum Technologies	Analysis of collision shift assessments in ion-based clocks
B22	249	Dr. Dohyeon Kwon	Kriss	Performance comparison of photonic microwave generated via optical frequency division and cryogenic sapphire oscillator at KRISS
B23	291	Miss Rebecca Allen	National Physical Laboratory	Improvements to the uncertainty evaluation of NPL-Sr1
B24	273	Mr. Moritz Eisebitt	Ferdinand-Braun-Institut gGmbH	Development of an optical two-photon clock for space
B25	303	Dr. Jan Hrabina	Institute of Scientific Instruments CAS	Long-term Performance of Iodine Absorption Cells
B26	290	Dr. Piotr Morzyński	Nicolaus Copernicus University	Transient sensitivity of optical atomic clocks and prospects for active-clock–based detection schemes
B27	319	Dr. Vojtech Svak	Institute Of Scientific Instruments Of The Cas, V. V. I.	Towards V-UV countinuous-wave laser source for precision time and frequency metrology
B28	306	Dr. David Fehrenbacher	Spacetech Gmbh	The Galileo Iodine Clock
B29	318	Mr. Adam Cepil	ISI of the CAS	New calcium optical frequency standard characterization in comparison campaign

Poster session 2 – Thursday April 23 - 15:30 – 17 :00 • Poster areas – Atrium & B9

Poster	Paper	Presenting Author Names	Organization	Paper Title
A1	228	Mr. Tung Thanh Thai	INRiM	Almost unattended time scale based on a single commercial cold Rb atomic clock
A2	239	Wu Dan	National Time Service Center	Stability Analysis of TWSTFT and PPP Time Transfer Links Based on the Three-Cornered Hat Method
A3	69	Miss Sufang Liu	National Time Service Center, Chinese Academy of Sciences	Research on Atomic Time Algorithm with Temperature Compensation
A4	53	Dr. Jian Zhang	National Time Service Center, Chinese Academy of Sciences	Autonomous Timekeeping for the Constellation Composed of LEO Satellites and BeiDou-3 Satellites
A5	61	Eng. Michael Kimmer	Universität der Bundeswehr München	A Galileo-Based Pseudolite System for Improving GNSS Time Transfer
A6	62	Dr. Vincent Crozatier	Thales Research & Technology	Broadband optical frequency stability transfer with an AOTF
A7	222	Dr. Jasmine Zidan	The University of Warwick	A Survey of PNT Standards for GNSS Based Applications: Landscape, Gaps, and Implications
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A41	99	Mr. Markus Kromrey	Physikalisch-Technische Bundesanstalt (PTB)	Integration of new technologies into Paul trap based clock experiments
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B8	32	Mr. Tingxuan Xiang	Peking University	Research on shared laser cesium atomic clocks
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B10	108	Mr. Shilong Feng	Beijing Institute of Radio Metrology and Measurement	Simulation of the radio frequency field of the 199Hg+ ion microwave clock and cooling with different buffer gases
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B18	47	Prof. Adarsh Ganesan	Bits Pilani, Dubai Campus	Analysis of Run-to-Run Variability in Compressional Acoustic Wave Responses from a Single Water Droplet Using Quartz Crystal Microbalance
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B29	340	Mr. Oliver Fartmann	Humboldt-Universität zu Berlin	Ramsey-Bordé Interferometry with a Thermal Strontium Beam for a Compact Optical Clock
B30	262	Dr. Sean Dyer	University of Strathclyde	Dark State Interference in Raman-Ramsey Coherent Population Trapping Clock: A Density Matrix Simulation Perspective
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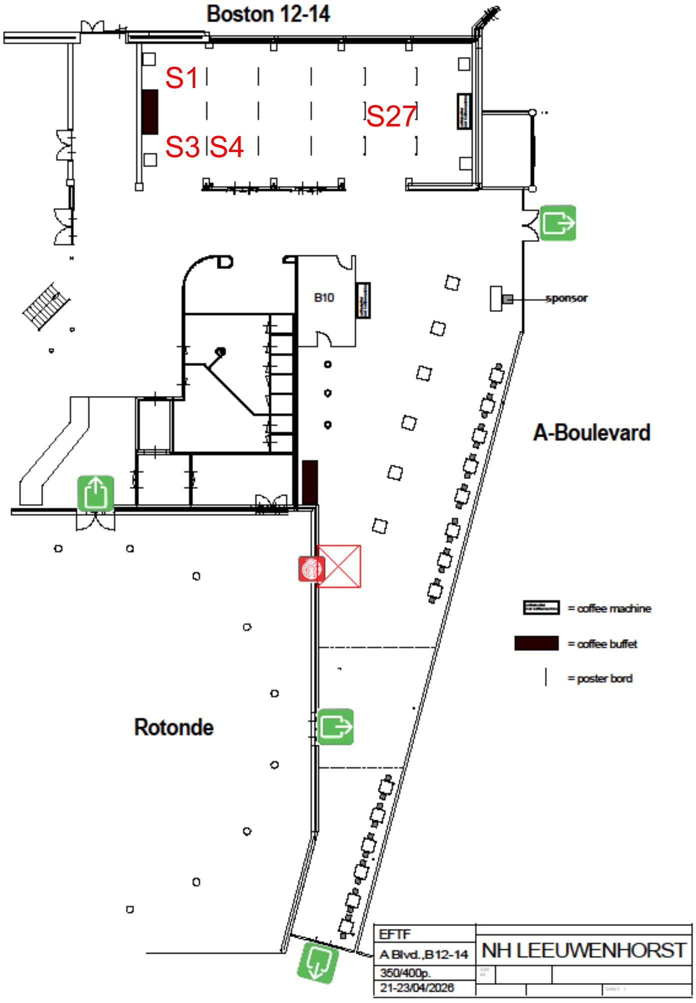

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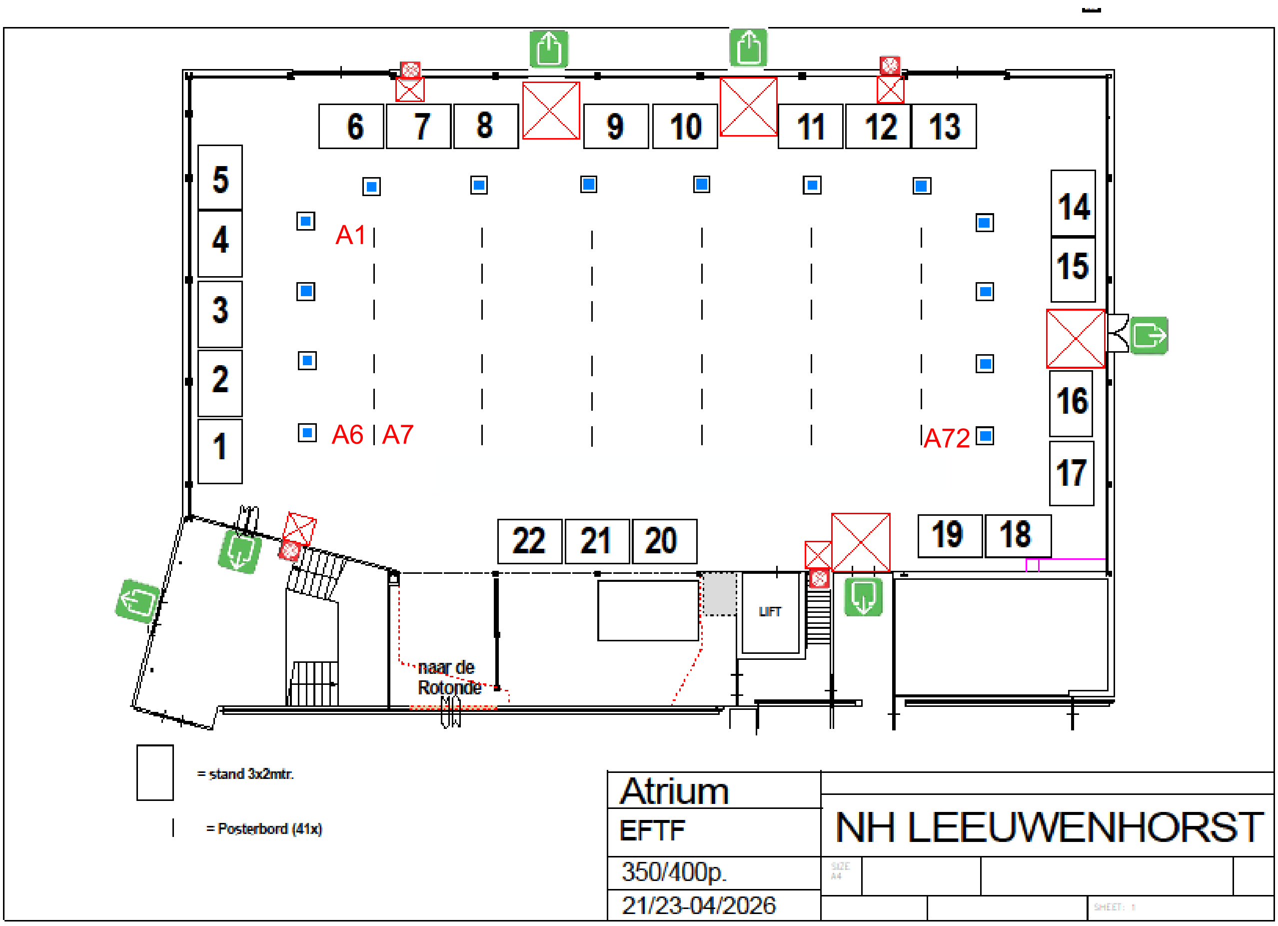

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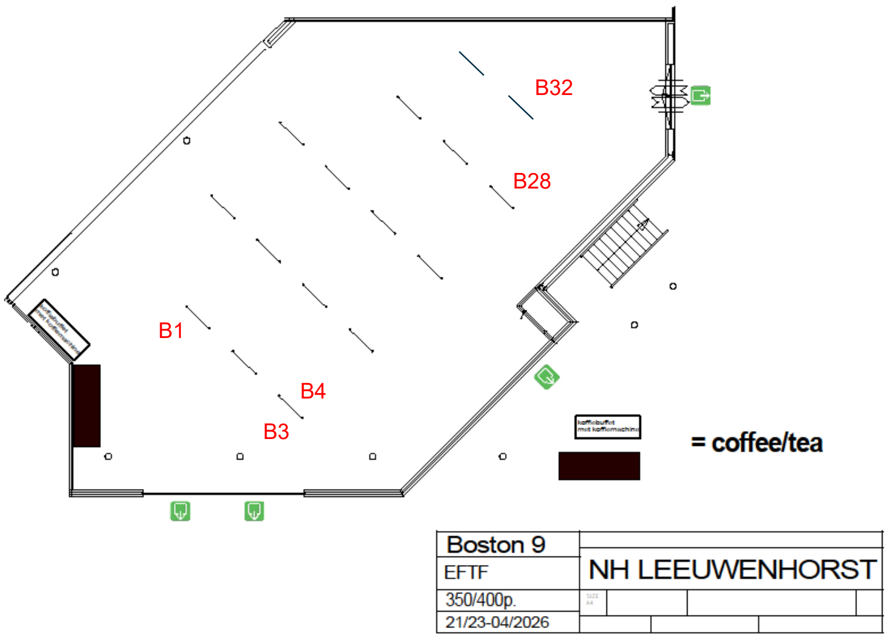

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LaLI-POP Frequency Stability and Light Shift: Phase-1 Testbed

Dr. James Camparo[1], Mr Michael Huang
[1]The Aerospace Corporation

G3: Vapor-cell deployable clocks, April 23, 2026, 13:30 - 15:00

Arguably, the vapor-cell atomic clock is the workhorse of precise timekeeping in space. However, the present-day Rb atomic frequency standard (RAFS) has two clear deficiencies: 1) its short-term stability is limited by weak optical pumping, and 2) its long-term stability can be limited by light-shift induced frequency noise. In both cases the limitations trace to the use of an rf-discharge lamp for atomic signal generation and monitoring. Though replacement of the lamp by a pulsed diode laser can eliminate these problems, the novelty of laser use in the RAFS presents space-systems engineers with a dilemma: trading better clock performance against potentially decreased clock reliability. Here, we discuss progress on development of the Lamp and Laser Integrated Pulsed Optically Pumped clock (LaLI-POP), which is a "bridge technology" that can solve the system engineer's dilemma.

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A continuous-wave 148.4 nm laser for a Th-229 nuclear clock

Prof. Shiqian Ding[1]
[1]Tsinghua University

G6: Advanced optical clocks, April 21, 2026, 13:30 - 15:00

The exceptionally low-energy isomeric transition in Th-229 at around 148 nm offers a unique opportunity for coherent nuclear control and the realization of an ultra-stable nuclear clock. Recent advances, most notably the incorporation of large ensembles of Th-229 nuclei in transparent crystals and the development of pulsed vacuum-ultraviolet (VUV) lasers, have enabled initial laser spectroscopy of this transition. However, the absence of an intense, narrow-linewidth VUV laser has been a critical missing element.

In this talk, I will present our proposal [1,2] and experimental realization [3] of the first continuous-wave laser at 148 nm, generated via four-wave mixing in cadmium vapor. Our source delivers more than 100 nW of power with a linewidth well below 100 Hz and supports broad wavelength tunability. We develop a spatially resolved homodyne technique to place a stringent upper bound on the phase noise induced by the nonlinear process and demonstrate sub-hertz linewidth capability. This development eliminates the final technical hurdle to a Th-229-based nuclear clock and opens new frontiers in quantum metrology, nuclear quantum optics and precision tests of fundamental physics.

[1] Q. Xiao, G. Penyazkov, R. Yu, B. Huang, J. Li, J. Shi, Y. Yu, Y. Mo, S. Ding, “Proposal for the generation of continuous-wave vacuum ultraviolet laser light for Th-229 isomer precision spectroscopy”, arXiv: 2406.16841 (2024)
[2] G. Penyazkov, Y. Yu, L.V. Skripnikov and S. Ding, “Theoretical study of transition matrix elements in cadmium for vacuum-ultraviolet generation in Th-229 nuclear clock applications”. Physical Review A, 112, 022807 (2025).
[3] Q. Xiao, G. Penyazkov, X. Li, B. Huang, W. Bu, J. Shi, H. Shi, T. Liao, G. Yan, H. Tian, Y. Li, J. Li, B. Lu, L. You, Y. Lin, Y. Mo, S. Ding, “A continuous-wave vacuum ultraviolet laser for the nuclear clock”, arXiv: 2507.19449 (2025)

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2025 update to the CIPM list “Recommended values of standard frequencies”

Dr. Helen Margolis[1], Francesca Collini[2], Tetsuya Ido[3], Andrew Ludlow[4], Gianna Panfilo[2], Marco Pizzocaro[5], Roxanne Siadat[1], Sebastien Bize[6]
[1]National Physical Laboratory (NPL), [2]Bureau International des Poids et Mesures (BIPM), [3]National Institute of Information and Communications Technology (NICT), [4]National Institute of Standards and Technology (NIST), [5]Istituto Nazionale di Ricerca Metrologica (INRIM), [6]Laboratoire Temps Espace (LNE-OP), Observatoire de Paris, Universite PSL, Sorbonne Universite, Universite de Lille, LNE, CNRS

G5+G6: Redefinition of the second, April 23, 2026, 13:30 - 15:00

When secondary frequency standards contribute data for calibration of the scale interval of International Atomic Time (TAI), they do so using the associated frequency value and uncertainty given in the CIPM list “Recommended values of standard frequencies”. These values are derived from an analysis of the global body of clock comparison data, using two independent algorithms, and periodically updated when significant new data is available. This presentation will describe the most recent update to the recommended frequencies, approved by the Consultative Committee for Time and Frequency (CCTF) in September 2025.

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Laser fractional frequency instability below 6×10^-17 with room temperature optical reference cavities

Dr. Marco Schioppo[1], A. L. Parke[1], E. Clulow[1]
[1]National Physical Laboratory (NPL)

G6+G2: Ultrastable lasers, April 23, 2026, 08:45 - 10:15

Ultrastable lasers play a key role in setting the measurement speed and precision of optical clocks, greatly facilitating clock accuracy characterisation. With the aim of supporting the optical clocks in reaching the targets of the roadmap for the redefinition of the SI second, we have been focusing on the development of ultrastable lasers with state-of-the-art stability performance, continuous operation, simplicity of use and construction, and no maintenance. For the above reasons, we have realised ultrastable lasers based on two 48.5 cm long and one 68 cm long optical reference cavities, operating at room temperature and with estimated thermal noise limits at 6×10^-17, 4×10^-17, and 3×10^-17, respectively. Here we report on the progress of the characterisation of the lasers' performance using three-cornered hat measurements showing fractional frequency instability below 6×10^-17, achieved with continuous operation and linear drift below 20 mHz/s. We will discuss present limitations and strategies to overcome them, with emphasis on reducing the impact of seismic noise and on extending state-of-the-art stability to longer averaging times.

Low Noise Photonic Microwave Generation with Free-running Frequency Combs and Feedforward Correction

Dr. Takuma Nakamura[1,2], William Groman[3,4], Qing-Xin Ji[5], Oguzhan Kara[6], Benjamin Rudin[6], Anatoliy Savchenkov[7], Vladimir Iltchenko[7], Wei Zhang[7], Andrey Matsko[7], John Bowers[8], Florian Emaury[6], Kerry Vahala[5], Scott Diddams[3,4], Franklyn Quinlan[1,4]
[1]Time and Frequency Division, NIST, [2]Department of Electrical Engineering,CU Denver, [3]Department of Physics, CU Boulder, [4]Electrical, Computer and Energy Engineering, CU Boulder, [5]T. J. Watson Laboratory of Applied Physics, Caltech, [6]Menhir Photonics AG, [7]Jet Propulsion Laboratory, Caltech, [8]Department of Electrical and Computer Engineering, UCSB

G6: Optical frequency combs, April 22, 2026, 10:45 - 12:15

We demonstrate a major simplification of two-point optical freqeuncy division that allows us to use most comb sources. Using free-running combs, we generate low noise, servo-bump-free microwave signals. We achieve 10 GHz phase noise of -153 dBc/Hz at 10 kHz with a 10GHz solid-state laser and 145 dBc/Hz at 10kHz (scaled to 10GHz) with a 20 GHz microcomb.

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Free-space time transfer between Yb Lattice Clocks on Mt. Bluesky (elevation 4300 m) and NIST (elevation 1650 m)

Dr. Emily Caldwell[1], Roger Brown[1], Christopher Dennis[1], Jean-Daniel Deschenes[3], Scott Diddams[2], Fabrizio Giorgetta[1], Tanner Grogan[1,2], Adam Halaoui[1], Benjamin Hunt[1,2], Andrew Ludlow[1], Harikesh Ranganath[1], Laura Sinclair[1], William Swann[1], Eric Swiler[1,2], Theodora Triano[1,2], Skyler Wright[2], Derek Van Westrum[4], Tsung-Han Wu[2]
[1]NIST, [2]University of Colorado, [3]Octosig Consulting, [4]NOAA

G5: Free space links & timescales, April 21, 2026, 10:45 - 12:15

We present results from the first experiment comparing a transportable neutral Yb optical lattice clock on the summit of Mt. Bluesky (elevation 4300 m) to a laboratory Yb clock on NIST cam-pus in Boulder, Colorado (elevation 1650 m). Each clock has its own atomic physics package and 1156nm cavity-stabilized laser1,2. This comparison was performed over an optical network consisting of a 69 km free-space link3 and an 81 km fiber link. Separately, geodetic surveying using state-of-the-art GPS systems was performed. Initial data processing indicates the measured gravitational redshift is consistent with the ~2700 m height difference.

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A new limit on real-time noise-cancelled fiber links

Dr. Charles McLemore[1], Dr. Marco Pomponio[2], Dr. Takuma Nakamura[1,3], Yifan Liu[1,3], Dr. Nazanin Hoghooghi[1], Prof. Antonio Mecozzi[4], Dr. Franklyn Quinlan[1,3]
[1]National Institute Of Standards And Technology, [2]Temporis Solutio LLC, [3]University of Colorado, [4]University of L'Aquila

G5: TFT in optical fibers 2, April 23, 2026, 10:45 - 12:15

Accurate real-time suppression of environmental path length fluctuations is essential for the delivery of precise optical signals through deployed fibers. This is done by double-passing the light through the fiber and generating a compensating phase that is proportional to one-half the measured roundtrip noise. This feedback imposes a well-known limit on how well the noise of the fiber at the remote end can be suppressed in real-time. Here, we show that the universally accepted limit can be improved upon by adding to the correction signal an appropriately weighted delayed version of itself in a digital signal processor. For a fiber with spatially uniform noise, the noise can be suppressed an additional 6 dB over the accepted limit; for noise that is localized along the fiber path, the suppression improvement can easily exceed 10 dB. We experimentally demonstrate improved noise performance over a 5.5 km deployed optical fiber in Boulder, CO, shown in Fig.1. Significant noise reduction beyond the accepted limit is seen across a broad range of offset frequencies. Experiments with localized fiber noise, theoretical analysis, and extensions to this technique will also be presented.

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Upper Side Band Syntonization and Synchronization concept of a set of N Satellites

Dr. Manuel Martin-Neira[1], Mr. Roger Vilaseca[2], Ms. Montserrat Puertolas[2], Mr. Albert Catalán[2], Mr. Volodymyr Kudriashov[1], Mr. Natanael Ayllon[1]
[1]ESA, [2]SENER

G2: Phase-frequency comparisons and analysis, April 23, 2026, 10:45 - 12:15

Imaging the event horizon of supper-massive black holes through sub-millimeter wave space-to-space very long baseline interferometry (VLBI) across a constellation of satellites in MEO, achieving high angular resolution in passive Earth observations at L-band with a formation of LEO satellites, or synthetic beamforming of a swarm of satellites that must work cooperatively to synthesize a larger aperture for telecommunication, exemplify applications that require syn-tonization and synchronization of a set of N≥2 satellites operating in-concert. Achieving precise syntonization and synchronization among satellites is challenging because, in general, they move relative to each other under different gravitational potentials and, consequently, both special and general relativistic effects appear which tend to prevent reaching this goal.
A method is presented to syntonize and synchronize N satellites. The method is sufficiently ro-bust against both relativistic Doppler and the Shapiro time delay, for the above-mentioned applications. The lack of syntonization and syntonization capability between clocks placed at different gravitational potentials cannot be avoided by the method. Hence, only in applications involving satellites at sufficiently similar gravitational potentials, or at different potentials performing measurements of a limited duration can the method be successfully employed. Fortunately, the referred fields involve spacecraft at roughly same orbital altitude, and the approach works well. Applying the method to other specific situations as the time alignment between a satellite and a ground station, or between a planet explorer mother spacecraft and a probe released towards its surface, require dedicated analysis, the result depending critically on the duration of the event and the gravitational difference between the two clocks.
The method is extremely simple, based on adding the frequencies of all clocks locally on each spacecraft, after a sub-set of these is received in one direction of a cycle passing through all the nodes, and the rest being received in the opposite direction along the same cycle [1]. Under the assumption that the local clocks of all spacecraft have a similar nominal frequency, but which can freely drift over time according to its quality, the so-obtained sum frequency at all spacecraft oscillates with the same frequency and phase (or with a constant phase difference which can eventually be calibrated out). In other words, all clocks are syntonized and synchronized when they are at sufficiently similar gravitational potentials as explained before. Because the concept is based on the addition of frequencies by retaining the upper side band of a mixer output, it has been named USBS (Upper Side Band Syntonization/Synchronization method).
The presentation will include the successful results obtained in the Microwave Laboratory of ESTEC of a two-node USBS demonstrator at 90 GHz for space-to-space VLBI application [2], and the results of a three-node industrial breadboard for high-resolution L-band radiometry. Moreover, a yet simpler USBS+ extension to N satellites of the method will also be introduced which is currently under development.
[1] Martin-Neira et al., Syntonisation of signals between satellites. Patent WO/2023/147885
[2] Kudriashov et al., Laboratory Demonstration of the Local Oscillator Concept for the Event Horizon Imager, Journal of Astronomical Instrumentation, Dec-2021.

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Progress on the Space-to-Ground Laser Time-and-Frequency Transfer Link Experiment for the China Space Station

Eng. Ning Yu[1], Eng. Xiao Wang[1], Dr. Shuaihe Gao[1], Mr. Shengkai Zhang[1]
[1]National Time Service Center

G5: Optical TFT in space, April 22, 2026, 10:45 - 12:15

The China Space Station is equipped with high-performance instruments including a strontium optical lattice clock, an active hydrogen maser and a microwave clock. To enable time compar-ison with ground-based clocks, the station carries a laser time-and-frequency-transfer payload composed of laser retro-reflectors, single-photon detectors and event timers. In parallel, the Na-tional Time Service Center (NTSC) has established two satellite-laser-ranging (SLR) ground terminals: one at the NTSC Space-town campus in Xi'an and the other at the Miyun Space Ap-plication Center campus in Beijing. The Xi'an terminal is built into a road-transportable con-tainer that can be relocated for campaign observations when required. Together, the on-orbit payload and the two ground terminals form a complete, high-precision and high-stability space-to-ground laser time-and-frequency transfer system. Both stations have already successfully tracked the laser time-transfer payload on the space station and acquired valid data, laying the foundation for subsequent laser time-transfer studies.
This paper reports the latest advances in the space-to-ground laser time-and-frequency transfer (L-TFT) system of the Chinese Space Station. We describe in detail the key components and enabling technologies of the two satellite-laser-ranging (SLR) ground terminals developed by the National Time Service Center, Chinese Academy of Sciences, and analyse the results of the first high-repetition-rate international space-to-ground L-TFT experiment carried out between these terminals and the station payload. The experiment lays the groundwork for evaluating the frequency signals of the on-board atomic clocks and for future tests of the gravitational red-shift.Space-to-ground two-way laser time transfer works by firing laser pulses from a ground station toward the satellite and synchronously recording the pulse arrival times at both the spacecraft and the ground terminal, thereby deriving the epoch difference between the two clock systems. Compared with microwave links, laser signals offer much higher carrier fre-quencies and are far less affected by the ionosphere; consequently, laser time transfer has be-come a mature technique that presently delivers the highest accuracy for space-to-ground clock comparisons.

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Fourier-Embedded Neural Networks for Clock Transition Spectroscopy Reconstruction

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G3: Frontier microwave-clock topics, April 21, 2026, 13:30 - 15:00

Precise locking of the clock transition frequency is crucial for the stable operation of atomic clocks. However, Clock Transition Spectroscopy (CTS) under electromagnetic excitation is highly susceptible to noise. This complicates the identification of atomic resonance peak and reduces the frequency-locking accuracy, thereby limiting the clock's frequency stability.
In this work, we demonstrate a high-fidelity reconstruction of CTS based on a Fourier-embedded neural network, as illustrated in Fig. 1. The encoder maps the detuning Δ between the atoms and the microwave field into a high-dimensional frequency-domain embedding via a sin–cos transformation, allowing the model to efficiently capture both oscillatory details and envelope variations2. A compact three-layer feedforward network then reconstructs the de-noised signal. To further enhance physical fidelity, a joint amplitude–gradient loss is applied to suppress unphysical oscillations and preserve the intrinsic symmetry of the CTS by constrain-ing deviations in the derivative distribution.
We use a Ramsey fringe of a hot cesium beam to demonstrate the potential of this neural net-work in reconstructing atomic CTS. The cesium atomic beam has a drift distance of 0.215 m and a most probable velocity of 215 m/s. As shown in Fig. 2, under Gaussian white noise, the method improves the SNR by approximately 10 dB compared with raw noisy data and conven-tional Kalman filtering. Using this pure Ramsey CTS, we can identify the atomic resonance frequency more accurately, as indicated in the inset of Fig. 2. The neural network proposed here features a concise, parameter-efficient design and robust performance, offering a promising approach for high-fidelity reconstruction of atomic CTS.

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The SKA-MID Frequency Distribution System - Update

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G5: TFT in optical fibers 1, April 21, 2026, 13:30 - 15:00

The Square Kilometre Array is a major international project that will become the world's most sensitive radio telescope once operational at the end of this decade. It will consist of large arrays of antennas that work together through interferometry, which relies on extremely accurate and stable phase-coherent reference signals. These signals must reach each antenna in perfect synchrony so the arrays can combine their data with the precision required for high fidelity science. Any loss of coherence reduces data quality, dynamic range, and the ability of the telescope to detect faint astronomical sources.

For SKA-MID, which is the component located in South Africa, reference signals are distributed from a central processing facility to every dish along long stretches of overhead fibre-optic cable. Because these fibres span many kilometres in exposed environments, they experience temperature changes, wind, and mechanical disturbances that alter the phase of the transmitted signals. Even small variations accumulate over long distances and can significantly degrade system performance. To address these effects, the SKA uses actively stabilised frequency transfer systems that suppress fibre noise in real time and maintain signal coherence across the entire array.

Since 2011, the University of Western Australia has been responsible for designing, developing, and manufacturing the frequency distribution system used by SKA-MID. This system continuously delivers phase-stabilised and phase-coherent reference signals from the central facility to each receiving station on dedicated fibre links. The concept originated from earlier photonic local oscillator systems used in other observatories and has been refined through advances in frequency metrology as well as innovations developed within the team. Over more than a decade of research, prototyping, and testing, the system has matured into a robust technical solution that satisfies the demanding stability and reliability requirements imposed by the SKA.

The frequency distribution system spans a spiral network of optical fibres across a region approximately 3,000 kilometres in total length. It is implemented through roughly 190 modular transmit and receive units, with individual links extending up to 180 kilometres. Despite the large scale and environmental exposure, the system achieves excellent performance. It maintains more than 99% uptime, keeps coherence loss below 1% on 1000s timescales, and delivers residual frequency instability lower than 10^-16. Timing jitter remains below 35 femtoseconds, which ensures the high precision needed for interferometric observations.

Production of the system is now well advanced. Hardware for the first eight SKA-MID links has already been delivered to the SKA, positioning the project to achieve first light in December 2025. Full mass manufacture of the receiver modules is scheduled for completion in the first quarter of 2026, followed by mass manufacture of the transmit modules in 2027. During the period between these milestones, an interim configuration of the transmit system is being deployed on site. This temporary arrangement allows telescope commissioning to continue without delay and ensures that scientific operations can begin on schedule.

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International Optical Clock Comparisons Using the European Optical Fibre Network

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G6: Clock comparisons, April 22, 2026, 13:30 - 15:00

As the international community moves toward redefining the SI second based on optical clocks, verifying the global consistency of these clocks has become critical. We report on two large-scale international comparison campaigns, via the European optical fibre network carried out in 2022 for 40 days and in 2023 for 60 days. The optical fibre network connected INRIM (Italy), LNE-OP (France), NPL (UK), and PTB (Germany) and was augmented by additional satellite connections to VTT (Finland) and NMIJ (Japan). Twelve optical clocks operating in six countries were measured, including systems based on 115In+, 199Hg, 171Yb+(E2), 171Yb+(E3), 171Yb, 88Sr+, and 87Sr. In total, we report 54 frequency ratios with uncertainty from 4x10-18 to 3x10-16.
The data collected across the two campaigns enabled cross-validation within a uniquely large network of independent optical clocks. This helped identify and understand some technical issues while confirming the robustness of most results. Yet a few inconsistencies up to 1x10-16 persist, evident both within the reported data and relative to other measurements, motivating continued investigation and refinement of the network.
The European fibre network provides ongoing opportunities to compare optical clocks across countries with negligible link-related uncertainties and is evolving towards a permanent research infrastructure. The network is being extended to Poland, Belgium and the Netherlands, with another comparison carried out in 2025 and more planned in the future. Beyond metrology, clock and fibre networks provide capabilities across various scientific fields, including fundamental physics, quantum communication, and fibre sensing.

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Progressing towards a Continuous UTC

Dr. Patrizia Tavella[1], Dr Tetsuya Ido
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G5: Timescales, April 22, 2026, 15:30 - 17:00

The work of the Consultative Committee for Time and Frequency (CCTF) towards a continuous UTC will be described. The final decisions will be adopted by the General Conference on Weight and Measures in October 2026 concerning the new maximum value for the difference |UT1-UTC| and its implementation date, to ensure the continuity of UTC for centuries.

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2025 Carrier-phase Two-Way Satellite Time and Frequency Transfer measurements in Europe

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G5: Satellite based TFT, April 23, 2026, 08:45 - 10:15

In this work we present the second experiment between several European timing laboratories using the digital modem SRS developed by NICT for carrier-phase measurements as an alternative to the traditional code-phase usage in the current TWSTFT network.

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The Operation of the Primary Frequency Standard, PHARAO, in Space

Dr. François Xavier Esnault[2], Dr. Philippe Laurent[1]
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G3: Cold-atom deployable clocks, April 22, 2026, 10:45 - 12:15

The primary frequency standard, PHARAO, is operating in space since May 1st 2025, 10 years after its delivery. This laser cooled cesium atomic clock is the frequency reference of the ACES payload installed outside the Columbus laboratory of the International Space Station.
In this presentation, we will summarize the PHARAO commissioning experiments, which include the clock start-up and the fine-tuning of the clock cycle and its key parameters. As, in microgravity, the cesium atom launch velocity can be varied over more than one order of magnitude, the study of systematic shifts will be quite different from ground based fountains. A broad range of velocities and densities will be explored with the goal of reaching a frequency accuracy of 10-16.
We have recorded Ramsey resonance with a linewidth of 0.332 Hz, displaying a coherence time of 1.5 s for the Ramsey resonance and about 3 times narrower than in Earth fountains. For reaching a PHARAO frequency accuracy at the 10-16 level, we will acquire space to ground comparison data over the 3 coming years using the microwave link (MWL) installed in several National metrology institutes and equipped with cesium fountains, rubidium fountains or optical clocks.
After the commissioning phase, ACES will enter in 2026 in the science operation mode, where the various ACES scientific objectives will be addressed, including the redshift test and the intercontinental ground clock comparisons.

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High-Uptime 88Sr+ Optical Clock with 7.9×10−19 Uncertainty

Dr. Thomas Lindvall[1], Dr. Thomas Fordell[1], Dr. Kalle J. Hanhijärvi[1], Dr. Anders E. Wallin[1]
[1]VTT, National Metrology Institute VTT MIKES

G6: Optical clocks metrology, April 23, 2026, 10:45 - 12:15

The VTT MIKES 88Sr+ optical ion clock is based on a single ion trapped in an endcap ion trap. In March 2022, it participated, via GNSS link, in its first optical-clock comparison within the European ROCIT project. Recently, we measured the differential static scalar polarizability of the clock transition with a 3.5 times reduced uncertainty. Together with a detailed evaluation of the blackbody-radiation temperature and a low vacuum pressure, the reduced polarizability uncertainty enables an estimated total systematic uncertainty of 7.9×10−19, among the lowest reported to date. By stabilizing the remaining unstabilized optical fibers, this could be reduced further to about 6×10−19. We also carried out an absolute frequency measurement against International Atomic Time (TAI) that spanned 10 months with monthly optical-clock uptimes between 67% and 99% and yielded an uncertainty of 9.8×10−17, the most accurate frequency measurement published to date. The high uptime is achieved by automated re-cooling of the ion when it remains dark after a collision with a background molecule and could be further improved by automated ion reloading.

We also present results on the self-comparison instability of the clock operated with different interrogation sequences and with two different reference cavities for the clock laser. In addition, we present results on recent measurements of atomic parameters of the 88Sr+ ion.

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ACES Microwave Link in-orbit performance characterization

Dr. Marc Lilley[1]
[1]LTE, Observatoire De Paris

G5: Microwave TFT in space, April 22, 2026, 13:30 - 15:00

The Atomic Clock Ensemble in Space (ACES) mission aims to test Einstein's theory of General Relativity through high-precision time and frequency transfer between the PHARAO cold caesium clock onboard the International Space Station (ISS) and a worldwide network of ground clocks. Beyond the test of the gravitational redshift at the 10-6 level, ACES will contribute to the realisation of international timescales, and support chronometric geodesy through global clock comparisons.
The data analysis is conducted by the ACES data analysis groups at ESTEC and LTE using two independent pipelines, whose methodological differences allow for effective cross-validation. This talk presents the preliminary findings from both groups, demonstrating the MWL's capability to recover space-to-ground desynchronization in the lambda configuration with a stability approaching a few parts in 1E14 at 100 s in modified Allan deviation over a single ISS pass, compatibly with the noise expected from PHARAO clock.

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White Rabbit in Radio Interferometry

Mr. Paul Boven[1,2,6], Dr. Jeroen Koelemeij[3,4], Mrs. Chantal van Tour[3,4], Dr. Rob Smets[5,7], Dr. Rodrigo González Escudero[3], Prof. Huib Jan van Langevelde[1,2]
[1]JIVE, [2]Leiden Observatory, [3]Vrije Universiteit Amsterdam, [4]OPNT bv, [5]SURF, [6]CAMRAS, [7]TNO

G5: White rabbit, April 23, 2026, 13:30 - 15:00

We present our work in using White Rabbit for reference clock distribution in (very long baseline) radio interferometers. From measured ADEV values, and a novel expression for the coherence loss due to flicker phase noise, we predict the sensitivity loss due to the use of White Rabbit in an interferometer, as a function of the observing frequency. Our predicted coherence loss agrees well with our direct measurements in an SDR-based testbed. Assuming a 2% coherence loss budget, we show that the regular WRS-3/18 White Rabbit switch would be usable up to 3.5 GHz, and the Low Jitter Daughterboard raises this limit to 15 GHz.

We also show how to calibrate out the effects of chromatic dispersion on already deployed fiber in a way that is much more accurate and convenient than the established method. And we demonstrate the use of White Rabbit on an already deployed production fiber infrastructure, co-existing with high-speed data traffic.

Finally, we combine these methods and perform VLBI observations using two radio telescopes, connected by a 169km WR link on a production fiber network, and using bi-directional optical amplifiers.

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L-band Resonant Gap Surface Acoustic Wave Filter with Reconfigurable Potentialities for Space Applications

Dr. Tony Makdissy[1], Dr. Eric Michoulier, Dr. Thierry Laroche, Dr. Alexandre Clairet, Dr. Emilie Courjon, Dr. Florent Bernard, Dr. Saly Ndiaye, Dr. Sylvain Ballandras
[1]Soitec

G1: Materials and resonators, April 21, 2026, 10:45 - 12:15

Communication systems are now at the heart of our connected lives. The deployment of these systems with their evolution over generations can be facilitated by new reconfigurable architectures allowing wideband and multiband processing. Proposed solutions for controlling SAW filters are generally limited to some hundreds of ppm agility. The present contribution demonstrates the ability of resonant gap surface acoustic wave (RG-SAW) filters on Piezoelectric-On-Insulator (POI) substrates to enhance agility, allowing for continuous frequency adjustment or discrete frequency hopping of several percents by applying simple electrical changes to dedicated filter gratings. The RG-SAW filter consists of at least two interdigitated transducers (IDTs) separated by resonant cavities. The main advantages of this architecture are the compactness, the limited insertion losses and the sharp transition bands on each side of the pass-band. Depending on the number and dimensions of the center cavity gratings, it is possible to cover a relative bandwidth ranging from less than 1% up to several percents, which allows for meeting various applications requirements, particularly space telecommunication ones. In this work, a L-band RG-SAW filter with reconfigurable potentialities is designed and fabricated on a standard Connect POI substrate. The coupling region between the two IDTs includes one Bragg mirror separating two cavities. The architecture of the cavities is based on gratings similar to those of the IDTs, where half of the fingers are grounded while the other half are kept floating. Switching the above electrical conditions from floating to ground changes the phase of the wave, thus the filter central frequency. An acousto-electric-electromagnetic (AE-EM) co-simulation was carried out to simultaneously optimize the number of fingers in the coupling region and the pitch of the filter as well as its footprint. A first demonstration of the principle was achieved by manufacturing different versions of the same filter, modulating its cavity grating boundary conditions and showing the possibility for frequency hopping in the range 1636-1676 MHz. Measurements validated the simulated results. The measured agility is 40 MHz with a minimum insertion loss of 2.8 dB and rejection better than 22 dB.

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Resonant Sensors from 2D Materials

Prof. Peter G. Steeneken[1]
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G4: Micro and nano resonant sensors, April 22, 2026, 15:30 - 17:00

Besides providing a widespread method for time-keeping, the principle of mechanical resonance is the foundation behind some of the most precise sensing technologies. By reducing the mass and thickness of the mechanical element, unprecedented sensitivities can be reached. This positions atomically thin 2D materials as promising candidates for breaking limits in resonant sensors.

Here, we will present an overview of recent studies in our group into how nanomechanical resonance in 2D material membranes can be used as a sensitive probe for measuring pressure, sound and mass. Moreover, we show that it can be used to investigate thermal and magnetic properties of 2D materials, including phase transitions that are hard to study otherwise. Finally, we look at the role of nonlinearities in reaching the ultimate sensitivity limit of 2D material resonant sensors.

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Cryogenic Sapphire Oscillators:

From Concept to State-of-the-Art Microwave References and Commercial Products

Dr. Vincent Giordano[1]
[1]Cnrs Femto-st Institute

G2: Oscillators, synthesis, and noise, April 22, 2026, 13:30 - 15:00

We will present an overview of the development of Cryogenic Sapphire Oscillators (CSOs) at FEMTO-ST Institute, from early laboratory experiments to the commercialization of the ULISS-2G model. We will review the technological choices that led to the design of an ultra-stable oscillator achieving a short-term frequency stability of 3×10−15 with a total power consumption of 3 kW.
Beyond these results, particular attention will be given to the approach that enabled these performances, including the key design choices and the systematic investigation of limiting factors. We will also highlight recent advances in the field, including the demonstration of a CSO operating with a Gifford–McMahon cryocooler, an explanation of whispering gallery mode degeneracy, and recent work on the thermal sensitivity of the sapphire resonator.

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A Commercial Strontium Optical Lattice Clock with 250 liters

Mr. Takashi Muramatsu[1], Mr. Yuya Sakai[1], Mr. Kazuki Nigo[1], Ph. D. Tetsuo Furumiya, Mr. Koji Tojo
[1]Shimadzu Corporation

G6: Commercial optical clocks, April 23, 2026, 08:45 - 10:15

An optical lattice clock achieves a fractional frequency uncertainty of 10^-18 level and is a candidate for a redefinition of the SI second. We aim to use optical lattice clocks easily in various fields all over the world. We developed the world's first commercial strontium optical lattice clock with 250 liters as an all-in-one system. We reduced the volume of the clock and improved reliability and easy maintainability. In the result of synchronized comparison between two clocks, the fractional frequency uncertainty is confirmed to be 10^-18 level. We will present most recent results.

6

Realization of a Kuramoto Timescale

Hunter Kettering, Dr. Nate Ristoff, Dr. Daniele Monahan[1], Dr. James Camparo
[1]The Aerospace Corporation

G5: Free space links & timescales, April 21, 2026, 10:45 - 12:15

We have created a physical realization of a Kuramoto timescale employing five crystal oscillator clocks. Previously, we showed via simulation that the Kuramoto concept could be profitably applied to space system timekeeping. Here we show that the Kuramoto concept works with physical clocks. For space system timekeeping the advantage of Kuramoto is that an ensemble timescale can be created solely from nearest neighbor data, and that the clocks do not need to be statistically independent from one another.

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Timescale Accuracy When Steered Using Different Frequency Prediction Methods

Dr. Bin Jian[1], Dr. Scott Beattie[1]
[1]National Research Council Canada

G5: Timescales, April 22, 2026, 15:30 - 17:00

In this presentation we will discuss the limitation of the timescale accuracy when generated by steering a single active hydrogen maser using either atomic fountain clocks or optical atomic clocks. Two widely used frequency prediction methods are compared here for the timescale computation, i.e., the least squares regression linear fit and Kalman filter. Frequency simulation data of the masers and the reference frequency standards are generated according to their noise characteristics to compute the timescales. The study leads to a preliminary conclusion that the timescale accuracy generated by steering the maser using the optical frequency standards is limited by the flicker frequency floor of the current masers and can be improved with the maser flicker frequency floor at the level of 10^-17.

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Identification of Clock Ensemble Noise Parameters Using Differential Measurement Analysis

Dr. Jindrich Dunik[1], Dr. Ladislav Kral, Dr. Ivo Puncochar, Dr. Oliver Kost, Dr. Ondrej Daniel, Dr. Simona Simona Circiu, Dr. Bernardino Quaranta
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G2: Phase-frequency comparisons and analysis, April 23, 2026, 10:45 - 12:15

The paper addresses the critical problem of identifying unknown parameters of an atomic clock ensemble. The ensemble model is considered as a set of individual clock models, where each clock is described by a second-order linear stochastic state-space model. The paper presents identification procedure for model unknown parameters based solely on the availability of differential measurements - that is, the measured pairwise phase differences between a designated pivot clock and all other clocks within the ensemble. Specifically, each clock model is defined by the following set of unknown parameters: the variances characterizing the white frequency noise and random walk frequency noise, the drift, and the variance of the measurement noise. Special emphasis is also laid on estimating the cross-covariances between the differential measurements. We propose and detail two distinct identification methods, in both frequency and time domains, designed to estimate the unknown clock model parameters.

The accuracy of the identified sets of parameters and their suitability for combination algorithms are demonstrated on a simulation scenario/real data combining H-maser and caesium atomic clocks, where dataset was acquired at the ESA ESTEC Time Laboratory as part of the ESA project NAVISP-EL1-056.

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Consolidated accuracy budget of a cold-atom-based commercial microwave clock reaching 2×10-14

Dr. Luc Archambault[1], Ms. Floriane Sparma[2], Dr. Cédric Majek[1], Dr. Arnaud Landragin[2], Dr. Bruno Desruelle[1], Dr. Luca Lorini[2], Mr. BRUNO PELLE[1]
[1]Exail, [2]LTE

G3: Cold-atom deployable clocks, April 22, 2026, 10:45 - 12:15

We present results of commercial microwave clocks developed by Exail Quantum Systems (formerly Muquans). MuClocks are cold-atom-based turnkey products dedicated to continuous long-term operation. Frequency stability reaching 1×10-15 within 2 days and maintained over more than a month has been demonstrated on several instruments, competing with the frequency drift of the best masers (~1×10-16/day).

The key element in a MuClock is its copper cavity which is used in two different ways: to isotopically cool in this integrating sphere around 107 atoms to sub-Doppler temperatures and to interrogate the atoms with a microwave signal benefiting from a well-defined mode. Once cooled, atoms are interrogated during their free-fall by two microwave pulses separated by a Ramsey duration of TR = 40 ms. The |F=2⟩ atoms are finally detected in a vertical absorption column with a cycle repetition rate between 5 and 10 Hz.

In this contribution, we will present a consolidated accuracy budget reaching 2×10-14 in fractional frequency uncertainty. Control and evaluation of the systematic frequency shifts have been performed and are summarized in Fig. 1. Dedicated studies on the microwave phase transient shift and on the phase gradient shift will be highlighted, while latest improvements on the accuracy budget will be updated at the conference

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Improving the short-term stability of a coherent population trapping clock via a stimulated Raman transition

Dr. Sean Dyer[1], Dr. Rajnandan Choudhury Das[1], Prof. Erling Riis[1], Prof. Paul Griffin[1]
[1]Department of Physics, SUPA, University of Strathclyde

G3: Frontier microwave-clock topics, April 21, 2026, 13:30 - 15:00

In this presentation, we will discuss recent advancements in our cold-atom CPT clock. Here, the implementation of a stimulated Raman transition enables a resonant readout scheme similar to that used in microwave-interrogated clocks, leading to an improved signal to noise ratio. We further demonstrate that composite pulse sequences can effectively suppress the light shifts introduced by the Raman beams.

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Design of a MEMS-based photo-acoustic pressure sensor – Capacitive approach

Professeur. Jerome Juillard[1], Lyraie Rakotondratsimba, Alexis Brenes, Alain Bosseboeuf, Michael Bahriz
[1]CentraleSupelec - GEEPS

G4: Micro and nano resonant sensors, April 22, 2026, 15:30 - 17:00

In healthcare applications such as analysis of exhaled air for medical diagnosis, there is a need for low-SWaP-C, high-resolution, selective gas sensors capable of performing in real time. Re-cent years have seen the promising development of several approaches based on the joint use of photo-acoustic emission and (silicon) MEMS or quartz resonators . The ANR-funded ATLAS project investigates new concepts of photo-acoustic MEMS transducers in order to bridge the gap with existing quartz approaches. One of these concepts is the development of a narrowband acoustic pressure transducer based on a MEMS membrane separating a vacuum cavity from the gas mixture at ambient pressure (Fig. 1). Since one side of the device is vacuum-packaged, the acoustic force on the membrane is maximized, which makes up for the increased stiffness due to in-plane stretching (compared to air-operated approaches), and dissipation is minimized. The laser responsible for photo-acoustic emission is modulated at the membrane resonance fre-quency to generate the largest displacement for a given amount of acoustic pressure. In this pa-per, we focus on the design of the membrane and its transduction through out-of-plane capaci-tive transduction . We show how simple cleanroom processes can be used to fabricate the membrane, with moderately high Qs (several 100s to 1000s) and frequencies in the 10s of kHz range (Fig. 2), compatible with the relaxation times of several gases. The input-referred ther-mal noise resulting from membrane dissipation is shown to be in the range of 100s of nPa/Hz1/2, corresponding to 100s of fm/Hz1/2 of out-of-plane displacement noise. We show that, depending on oxide layer thickness, parasitics may prevent the optimal use of capacitive detec-tion and that a resonant means of detection may solve this issue .

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Progress on miniaturized laser-cooled 171Yb+ ion microwave clock

Miss Ying Zheng[1,2], Miss Wenxin Shi[1], Mr. Shuotian Chen[1], Mr. Binglu Yan[1], Mr. Tianjun Guo[1], Miss Yang Lin[1], Dr. Jianwei Zhang[1], Prof. Lijun Wang[1,2]
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G3: Frontier microwave-clock topics, April 21, 2026, 13:30 - 15:00

The ytterbium ion microwave clock, benefits from technologically mature and highly stable laser systems, offering a distinct advantage in the development of compact, integrated, and transportable microwave frequency standards. This paper presents the progress on miniaturized laser-cooled 171Yb+ ion microwave clock in Tsinghua University. The volume of the physical package is integrated to 47.09 L. The measured short-term frequency stability of the clock reaches $1.1\times10^{-12}/\sqrt{\tau}$, surpassing results previously reported by the National Physical Laboratory (UK) and the National Institute of Information and Communications Technology (Japan).

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Advances in Cross Correlation in Signal- and Spectrum Analysis

Dr. Florian Ramian[1], Dr. Michael Simon[1]
[1]Rohde & Schwarz

G2: Oscillators, synthesis, and noise, April 22, 2026, 13:30 - 15:00

Cross-correlation methods are a powerful class of measurement and processing techniques for extracting weak signals buried in noise and for improving the dynamic range of signal and spectrum measurements. They are widely used in phase-noise and oscillator characterization, where measurement-system noise frequently masks the device-under-test (DUT). By splitting the DUT output into two (or more) nominally independent measurement chains and coherently averaging the complex cross-spectrum, uncorrelated instrument noise averages toward zero while the DUT's correlated signal is preserved, allowing the measurable noise floor to be driven far below that of any single channel.

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Low SWaP Embedded Atomic Clocks for Space

Mr. Peter Cash[1], Mr. John Bollettiero, Mr. Robert Connors, Mr. Will Emanuel, Mr. Christopher Higgins, Mr. Igor Kosvin, Mr. Will Krzewick, Mr. Mike Silveira, Mr. Matt Stanczyk, Mr. Kevin Wellwood
[1]Microchip Technology

Poster session 1, April 21, 2026, 15:30 - 17:00

Embedded atomic clocks enable many space applications that require precise and autonomous frequency and time. Leveraging commercial off-the-shelf (COTS) components, the Space CSAC SA65 and Space MAC (8300C-LN) are suitable for many LEO and select MEO and Lunar applications. Our presentation will describe the design changes, performance, and ra-diation tolerance of these new, readily available atomic clocks, which are commercially li-censed and economical. Single Event Effects (SEE) are explored, and methods for recovering from SEE are presented.

The updated Space CSAC demonstrates total ionizing dose (TID) tolerance up to 30 krad (Si) with no measurable degradation in clock performance, extending its applicability to longer-duration space missions in LEO and beyond. Compared to its predecessor, the new design exhibits improved temperature stability, reducing maximum frequency change over its operat-ing range by 40% while increasing the operable temperature range. In addition, the new de-sign has improved lock time, phase noise, and voltage sensitivity.

The new Space MAC leverages the exceptional temperature stability and drift of the terrestri-al version to provide long-term holdover. The MAC is widely deployed in commercial and military avionic applications when the highest levels of accuracy and environmental resilience are required. The MAC exhibits temperature stability of less than 5 x 10^-11 over the -40°C to 75°C temperature range. The frequency stability of the space MAC is suitable for many emerging PNT applications. The variant includes a low-power OCXO, Microchip's EMXO, to provide excellent phase noise and short-term stability of less than 2×10^-12. Both atomic clocks support one pulse-per-second disciplining and timekeeping.

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Innovative TCF Compensation Architecture for Bulk Acoustic Resonators

Mr. Florian Hartmann[1], Prof. Luis Guillermo Villanueva[1]
[1]EPFL NEMS

G1: Materials and resonators, April 21, 2026, 10:45 - 12:15

Lithium niobate (LN) thin films enable wideband RF filters thanks to their high intrinsic electromechanical coupling (k^2) and frequency scalability. However, their large temperature coefficient of frequency (TCF) of −90 to −110 ppm/K remains a major limitation. Existing TCF compensation strategies using SiO_2 overlays/underlays in plate-wave resonators or XBARs are not compatible with thickness-excited YBAR/FBAR devices, as a continuous oxide layer disrupts vertical fields and suppresses coupling. In LN FBARs, TCF values remain around −105 ppm/K with TCF improvement attempted by using other cuts or left as pending work.
We propose a new TCF-compensation architecture for YBAR resonators where SiO_2 is locally buried inside the LN layer. Unlike surface oxide approaches, this geometry keeps the electrodes in contact with the LN, preserves thickness-mode excitation, and locally balances elastic and dielectric contributions. Simulations show that a 30% oxide fill reduces TCF from −98 ppm/K to −50 ppm/K while still maintaining 18% coupling. To fabricate the devices, SiO_2 is selectively deposited into LN trenches (sub-wavelength pitch), then planarized and metallized. Experimental results confirm the simulated trends: devices with moderate oxide implantation achieved TCF values of –57 ppm/K with ~20% coupling, while more aggressive designs reduced TCF to –35 ppm/K at the expense of coupling (~9%). These results validate the buried oxide concept and highlight its potential impact for TCF reduction without fully sacrificing k^2.

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Absolute frequency measurement of 88Sr+ at the 10-16 level

Dr. Claude Marceau[1], Dr. Scott Beattie[1], Dr. Bin Jian[1], Dr. Kosuke Kato[1], Dr. Pierre Dubé[1]
[1]National Research Council Canada

G6: Ion optical clocks, April 21, 2026, 10:45 - 12:15

NRC-Sr+1 was the first single ion clock to be included1 in Circular T in early 2025. Nearly a year later, it was still not included in the steering of International Atomic Time because of the inaccuracy of the 88Sr+ CIPM 2021 recommendation. The scientific community was in need of additional high precision 88Sr+ measurements by July 1st 2025, to prepare the 2025 recommendation.

Answering the call, we made a 37-day measurement campaign comparing the frequencies of NRC-Sr+1 and NRC-FCs2 with 68% uptime over the months of October, November and December 2024. The use of optically referenced microwaves improved the NRC-FCs2 statistical averaging to σ_y = 6.3 × 10^(−14)/τ^(1/2). This comparison yielded f = 444 779 044 095 485.404 (46) Hz. A concurrent 30-day comparison to Terrestrial Time yielded f = 444 779 044 095 485.406 (89) Hz. Our results were included in the calculation of the new 2025 CCTF recommendation.

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A Doppler Simulator for Future Ground-to-Space Time and Frequency Transfer

Mr. Shawn Mcsorley[1], Dr Benjamin P. Dix-Matthews[1], Dr Andrew M. Lance[1], Professor Sascha W. Schediwy[1], Professor Fabrizio R. Giorgetta[2], Dr Jean-Daniel Deschenes[2,3], Professor Ian Coddington[2], Professor Laura C. Sinclair[2], Dr Emily D. Caldwell[2]
[1]International Centre For Radio Astronomy Research, [2]National Institute of Standard and Technology, [3]Octosig Consulting

G5: Optical TFT in space, April 22, 2026, 10:45 - 12:15

The comparison of optical frequency standards over ground-to-space free-space channels will empower next generation tests of fundamental physics, relativistic geodesy surveys, and the comparison of future optical clock ensembles between continents1. Measuring and tracking the Doppler shift in a ground-to-space link poses a significant challenge for future time and frequency transfer. Here we present a Doppler simulator (see Fig. 1), capable of simulating the expected Doppler shift
with closing velocities of ±11,000 m/s (±8GHz), for both a continuous-wave (CW) laser and optical frequency comb.

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Millimeter-wave Voltage Controlled Oscillators based on electronic bandgap material resonators for application in space

Dr. Enrico Lia[1], Dr. Indra S. Ghosh[2], Dr. Rüdiger Follmann[2], Mr. Horst Fischer[2], Dr. Stephen M. Hanham[3]
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G2: Oscillators, synthesis, and noise, April 22, 2026, 13:30 - 15:00

This paper introduces ultra-low phase noise novel oscillators based on electronic bandgap resonator for direct frequency synthesis at millimeter-wave frequencies operating at 46 GHz and 57 GHz for Earth Observation application.

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Integrated Si3N4 high Q Microring Resonators for Optoelectronic Oscillators

Mr. Zeeshan Ahmed[1]
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G1: Materials and resonators, April 21, 2026, 10:45 - 12:15

Optoelectronic Oscillators (OEOs) are used to generate spectrally pure microwaves frequencies with low phase noise. Conventional OEOs are bulky with the use separate elements for the laser, the modulator, the fiber optic delay line, the photodiode and the electrical amplifier. For that, integrated optoelectronic oscillator are a promising option in order to reduce the footprint . One of the space consuming and environment sensitive element is the fiber optic delay line that can be replaced by an integrated microring resonator providing a high Q factor. The approach we are exploring is based on a directly amplitude modulated single mode laser chip butt-coupled to a Si3N4 chip integrating a high Q ring resonator (Fig. 1). The work presented here is on the choice of the optimal circuit in terms of Q factor depending on the ring design parameters.

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A paper realisation of optically steered time scales at NPL

Dr. Daniela Weston[1]
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G6: Optical clocks metrology, April 23, 2026, 10:45 - 12:15

Improvement of the accuracy and stability of national time scales UTC(k) is critical for many applications, such as communication systems, satellite positioning, and fundamental research. The SI second is currently realised using caesium microwave standards with inaccuracies on the order of 10^-16. However, optical atomic clocks now surpass these standards, achieving uncertainties at the 10^-18 level. The SI second is expected to be redefined within the next decade, and the integration of optical clocks into national timing infrastructure will be required. Prototype optically steered time scales UTCx(k) have been realised by several laboratories by steering hydrogen masers using optical clock data. However, optical atomic clocks remain laboratory-based research systems and are not yet capable of sustained autonomous operation, making it necessary to understand how both the limited availability of optical clock data and the interval between maser steers affect the performance of the generated time scale.

A paper time scale approach involves post-processing optical clock data. By this analysis we can carry out numerical experiments and compare steering algorithm performance in each case with the existing physical time scale, which only has one mode of operation for each measurement campaign. In this work, we simulate optically steered time scales through steering the frequency of hydrogen masers, using data from NPL's state-of-the-art optical clocks. Due to the limitation of the optical clock data (< 2 months per measurement campaign), we focus on the effect of the steering interval in the generated optical time scales.

We use UTC and physical UTCx(NPL) time scales as references to evaluate the stability of the realised paper time scales. The physical UTCx(NPL) time scales have been implemented by measuring the frequency offsets of two hydrogen masers (NPL-HM5 and NPL-HM6) from NPL's Yb+ ion optical clock using an optical frequency comb and steering their frequencies every hour. We show that the resulting time scales remain align with UTC by less than 1 ns across two separate measurement campaigns.

The UTCx(NPL) paper time scale primarily focuses on two variables: the steering interval and the steering predictions during periods of optical clock downtime. By choosing several steering intervals, we can determine if infrequent steering can introduce additional maser noise – which is much greater than the noise of the optical clock – thus deteriorating the resulting UTCx(NPL) stability. The residual offset between the paper and physical time scales varies between 0.05 ns and 0.2 ns for intervals between 1 hour and 12 hours, respectively, and we will also show how this compares against UTC. Lastly, we will demonstrate alternative methods for predicting maser behaviour by incorporating ultra-stable cavity data during short periods of clock downtime.

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Onboard ensemble timescale realization for synchronization of future G2G-like constellations

Mr. Christian Trainotti[1], Dr. Lotfi Massarweh[2], Manuele Dassié[1], Giulia Schievano[1], Dr. Gabriele Giorgi[1]
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G5: Timescales, April 22, 2026, 15:30 - 17:00

Next generation Global Navigation Satellite Systems (GNSSs) will most likely benefit from inter-satellite links (ISLs). ISLs enable the generation of ranging observables between satellites, as well as performing time transfer, and they provide a data relay function across the GNSS constellation. Thanks to these capabilities, a paradigm shift is possible for the autonomous realization of a system timescale. Instead of a ground-based realization of the timescale, where each satellite clock offset is estimated, an onboard realization of the timescale and estimation of the clock offset is enabled by the relay of time offset measurements obtained via ISL. These are processed onboard each satellite by an algorithm establishing a distributed clock ensemble, composed of all the satellites in the constellation. In this way, each onboard clock can be directly aligned to the constellation system time. Assuming a real-time distribution of the ISL observables across the constellation, an autonomous synchronization of all satellites can be achieved.

This work analyzes the feasibility of such a scheme in a Galileo 2nd Generation (G2G) scenario and presents the achievable synchronization level. G2G will be equipped with radio-frequency ISLs establishing a dual one-way data exchange between pairs of satellites. After the data exchange, the link topology is changed to connect to a different satellite. This design introduces some constraints on the proposed onboard synchronization scheme: firstly, compared to a two-way time transfer, the time division of the G2G link impacts the achievable time transfer accuracy by limiting the synchronism of the time exchanges. Secondly, the real-time distribution of observables is not guaranteed, since only one link per satellite is established at any epoch. Instead, the data is distributed in a multi-hop fashion using the “flooding by broadcast” approach. Thus, each satellite only receives a subset of measurements with different delays. Processing these measurements on board results in different local computations of the system timescale, thus degrading the satellite synchronization.

In this work, we firstly generate realistic G2G time offset observables by: 1) estimating the achievable performance of the time transfer in a G2G scenario assuming the G2G data exchange design and predicted orbit information; 2) simulating the distribution of the observables using a dedicated scheduling algorithm considering the G2G link constraints; and 3) generating time offset observables using simulated G2G clocks or equivalent measurements of real atomic clocks in a laboratory.

Then, with this data we assess the performance of a real-time onboard synchronization scheme. The scheme makes use of a local computation of a distributed clock ensemble based on Kalman filtering using the time offset measurements locally received. The performance of the proposed method is evaluated in terms of achievable real-time synchronization error between satellites, continuity of the generated timescale, as well as computational and data transfer needs. Finally, the performance is compared to a benchmark scenario, implementing a batch Kalman filter making use of all the available measurements. This last case represents a post-processed, ground-based timescale generation using all the collected inter-satellite observables.

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Multi-Constellation IPPP Link for UTC

Dr Jiang Guo[1], Dr. Giulio Tagliaferro[1]
[1]BIPM

G5: Satellite based TFT, April 23, 2026, 08:45 - 10:15

GNSS-based techniques remain the primary method for global clock comparisons. Over recent decades, Precise Point Positioning (PPP) has emerged as a standard approach for accurate GNSS time transfer and is used in Circular T since 2009. More recently, Integer ambiguity-resolved PPP (IPPP) for GPS has further improved performance, achieving frequency transfer stability on the order of 10^{-17} with extended averaging. IPPP implementations using additional constellations such as GALILEO and BDS are now common in the geodetic and positioning communities and hold strong potential for high-precision time transfer applications as well.

The outstanding stability of Optical Frequency Standards (OFS) is beginning to challenge the accuracy limits of GNSS-based frequency transfer, particularly those of PPP. Currently, PPP constitutes one of the largest uncertainty contributions in the calibration of UTC by Primary and Secondary Frequency Standards (PSFS). As GALILEO and BDS are now fully operational, it is natural to extend existing time-transfer solutions to include these constellations, enhancing robustness and precision. Furthermore, the future discontinuation of semicodeless tracking of the GPS P1 and P2 signals may affect the long-term availability of precise bias products, reinforcing the need for multi-constellation approaches.

A multiday GNSS time transfer strategy based on Integer ambiguity-resolved Precise Point Positioning (IPPP) has therefore been developed using the PRIDE PPP and Atomium software packages. The solution has been tailored for potential integration into the BIPM's Circular T workflow. Its performance has been assessed using different rapid orbit and clock products—Wuhan rapid, CNES rapid, and CODE rapid solutions—and the effect of day-boundary discontinuities in these ephemerides has been carefully analysed. The method has been validated through comparison with Two Way Satellite time and Frequency Transfer (TWSTFT) time transfer data, optical fibre data and the current BIPM PPP solution, demonstrating its suitability for UTC use.

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Characterization of the Refimeve metrological signal 1000km from the source

Mr Mathieu Collombon[1], Mr Etienne Cantin[2], Mr Gaëtan Hagel[1], Mr Paul-Éric Pottie[3], Ms Marie Houssin[1], Ms. Caroline Champenois[1]
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G5: TFT in optical fibers 1, April 21, 2026, 13:30 - 15:00

Our lab in the south of France is receiving the ultrastable, absolute optical reference signal disseminated by the Refimeve infrastructure, through 1000 km of fiber from its source in Paris. We have carried out an analysis of the Refimeve signal quality that we are able to investigate using measurements based on the comparison between our local laser and the Refimeve signal in terms of fractional frequency instability, phase noise, and laser linewidth. With a focus on phase noise analysis, we identify a flicker frequency noise plateau at $2 \times 10{-}15$ on the local laser between 1 and 12 s. We then deduce from our measurement that the broadening of the spectral linewidth of the received Refimeve optical signal due to residual noise in the transfer is 6.2 kHz for an averaging time larger than 40 ms.

Ultra-low phase noise RF synthesis for Cs CPT atomic clock interrogation with an optoelectronic oscillator

Jimmy Pennanech[1,2], Dr Yohann Léguillon[1], Dr Arnaud Fernandez[2], Dr Olivier Llopis[2], Dr François Gutty[3], Dr Luc Leviandier[3], Josipa Madunic[3], Dr Ghaya Baili[3], Dr. Vincent Crozatier[3]
[1]Thales Land and Air systems, [2]LAAS-CNRS, [3]Thales Research & Technology

G2: Oscillators, synthesis, and noise, April 22, 2026, 13:30 - 15:00

Atomic clocks based on coherent population trapping (CPT) and operating with a Ramsey pulsed optical interrogation sequence of the RF hyperfine transition demonstrated impressive frequency stabilities of a few 10^{-13} at 1 s. In this pulsed interrogation scheme, the atomic clock becomes sensitive to the phase noise of the optically carried RF signal through the so-called Dick effect. This work describes a simple frequency synthesis to generate a RF local oscillator at 4.596 GHz whose estimated contribution to the relative frequency instability of the clock is 3×10^{-14} at 1 s.
We propose to use a 10 GHz OEO as the reference frequency instead of a low frequency OCXO. The OEO is carefully designed to exhibit ultra-low phase noise at low offset frequencies (-103 dBc/Hz at 100 Hz offset). The OEO then drives a frequency divider-by-2 on one side, and a digital synthesis on the other, which offers the required agility for Ramsey interrogation. The recombination provides the 4.596 GHz local oscillator for Cs interrogation with state-of-the-art phase noise performances.

Optoelectronic oscillator based on self-injection locking on a high quality factor fiber Fabry-Perot resonator

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G6+G2: Ultrastable lasers, April 23, 2026, 08:45 - 10:15

We report on an opto-electronic oscillator (OEO) at 10.17 GHz based on a fiber Fabry-Perot (FFP) resonator, made by depositing thin film mirrors with high reflectivity (R = 99,95 %) at both ends of an optical fiber section. The FFP has a length of 1 cm, a high-quality factor (Q = $9{,}58\times10^7$) and a free spectral range of 10.17 GHz. Compared to a classical delay line OEO, this architecture improves the system compactness, the FFP resonator replacing both the delay line and the microwave filter used for mode selection. However, the laser must be locked on one of the resonances of the FFP resonator. To this purpose, we use the self-injection locking approach with a semiconductor DFB laser without isolator. The phase noise of the OEO is then measured and shows a good agreement with our simulation, which allows us to identify the main noise contributors for further improvement of the system performance.

Frequency Reproducibility of Hyperfine Transitions in Iodine Vapor Cells for Optical Clock Technology

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G6: Deployable optical clocks, April 22, 2026, 15:30 - 17:00

Iodine-based quantum optical clocks show exceptional performance down to the 10-15 instability range and have been in the scope of researchers for decades with demonstration systems on ground and in space . The first systems of this clock type are now commercially available with a great demand by the civil and security sectors. These clocks are also prime contenders for next generation GNSS due to their superior performance compared to the currently used micro-wave clocks on GNSS satellites while keeping relatively low complexity and size, power and mass. While many key aspects of such clocks have been thoroughly investigated, the reproduci-bility of the heart of the system – namely the iodine vapor cell – has not yet been in the scope of researchers, likely because the development of such clocks is usually individual prototypes. Within the COMPASSO space-clock project, we investigated 9 identical vapor cells which were thoroughly characterized. Our research highlights points such as the reproducibility of the clock frequency, performance and aging effects of 9 cells, which have been produced over a timeframe of 5 years in individual production runs, proving the reproducibility and durability of the cells.

We find a frequency difference below 1 kHz for all cells, corresponding to 3x10-12 in accuracy. This level of uncertainty is below the uncertainties of other iodine vapor setups reported in lit-erature. A change of the absolute frequency due to aging could not be observed using cells be-ing produced one month to 5 years prior to the measurement. Overall, we conclude that the manufacturing and characterization process ensures a high reproducibility of iodine vapor cells used for optical clock technology and aging effects are minimal.

Within this presentation we will also highlight the latest developments within the COMPASSO project and the results of the qualification campaign. The iodine reference qualification model reaches an 5x10-15 instability at 1000s and successfully underwent TVAC and vibra-tion (20 grms) testing.

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Frequency ratios with NPL 171Yb+ optical frequency standard

Dr. Rachel Godun[1], Dr. Alexandra Tofful[1], Mr Patrick Regan[1]
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G6: Clock comparisons, April 22, 2026, 13:30 - 15:00

We will present the results of measuring both unit and non-unit optical frequency ratios with the NPL 171Yb+ optical frequency standard (NPL-E3Yb+3). These include local ratios at NPL, measured against the strontium optical frequency standard (NPL-Sr1), as well as remote ratios against optical frequency standards in other countries, carried out over satellite and optical fibre links.

Since the publication of the uncertainty budget for the NPL 171Yb+ standard, small improvements have been made to the evaluation of the electric quadrupole shift, bringing the total estimated systematic uncertainty to below 2 × 10−18. The statistical uncertainty has also been reduced, with improvements to the coherence of the atom-laser interaction as well as increased operational uptimes. Together, these improvements have enabled both local and remote frequency ratios with the NPL 171Yb+ standard to reach total uncertainties ≲ 5 × 10−18.

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Optically-pumped cesium beam clock with reduced cost by means of a cavity-integrated vacuum enclosure

Mr. Vladimir Dolgovskiy[1], Fabiano Kroll[1], Manuel Haldimann[1], Dr. Patrick Berthoud[1]
[1]Oscilloquartz SA

G3: Frontier microwave-clock topics, April 21, 2026, 13:30 - 15:00

One of the main purposes that the cesium beam clocks serve is to provide the reference frequency with an enhanced long-term stability that could be fed to multiple commercial devices. To achieve such a frequency stability the atoms in a thermal beam are specially prepared by experiencing a series of interactions with electro-magnetic fields along their trajectory with an overall goal to achieve a population imbalance of the hyperfine ground states. Traditional technology implies the magnetic deflection of the cesium beam with the strong permanent magnets onto the filament detecting the ionized atoms. Oscilloquartz has recently released its high-end optically pumped cesium beam clock (OSA-3300 SHP) where the atomic state is prepared by means of the optical pumping with a single narrow-band laser and the final state is detected using the same laser following the atomic interactions with the microwave field . This technology of optical pumping allows us to achieve a better frequency stability without any sacrifice in the clock life time.

With an increasing demand for the GNNS network densification and resilience of the critical infrastructure the cost reduction of the frequency standards becomes crucial. We have revisited a standard architecture of the cesium beam tube with the main clock components, such as cesium getters, microwave cavity, C-field coils, magnetic shields, cesium oven and collimation unit, embedded in a vacuum enclosure, by keeping only necessary components under vacuum while placing other components outside of the vacuum enclosure, namely oven heating elements, C-field coils and magnetic shields. Furthermore the vacuum enclosure now directly integrates the micro-wave cavity thanks to the recent advances of the additive manufacturing technology. This change allowed us to greatly simplify the clock manufacturing process and to decrease the overall product cost. The targeted stability of the deflected cesium beam clock (Microchip PRS-4400R-EP) 1.4e-11 tau-1/2 is ensured in all our low-cost clocks in production with the guaranteed lifetime of ten years. The frequency stability of the prototype clock is as good as 6e-12 tau-1/2.

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10-GHz broadband low-noise Er-doped solid-state optical frequency comb

Eng. Niccolò Salvatore Barberio[1], Dr Francesco Canella[2], Dr Andrea Pertoldi[3], Dr Benjamin Rudin[3], Dr Florian Emaury[3], Mr Francesco Benatti[1], Dr Dario Giannotti[1], Prof Francesco Leone[4], Prof Paolo Laporta[1,4], Dr Gianluca Galzerano[2,4]
[1]Politecnico Di Milano, [2]Istituto di Fotonica e Nanotecnologie - CNR, [3]Menhir Photonics, [4]INAF - Osservatorio astronomico di Catania

G6: Optical frequency combs, April 22, 2026, 10:45 - 12:15

Optical frequency combs provide a phase-coherent bridge between optical and microwave domains, advancing precision metrology, spectroscopy, and time-frequency transfer. We present a compact fully stabilized 10-GHz Er-doped solid-state frequency comb at 1.56 µm featuring two all-fiber amplification and compression stages. The first delivers 180-fs, 1.2 kW peak power pulses for f-2f interferometry and carrier envelope offset frequency detection; the second yields 1.9 kW peak power pulses driving coherent supercontinuum generation spanning from 1150 to 2350 nm using commercial Ta_2O_5 waveguides. The repetition rate and carrier envelope offset frequencies are phase-locked to an RF reference, and 1% of the oscillator is heterodyned with a narrow-linewidth cw laser. Future works will include visible supercontinuum generation, repetition rate doubling, and spectral equalization to realize an astrocomb spanning from visible to short-wave infrared. The system will be deployed at INAF’s Galileo National Telescope to calibrate HARPS-N and GIANO spectrographs, enabling precise radial velocity measurements for exoplanet detection.

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NOVEL HAMMER-SHAPED ELECTRODE DESIGN FOR XBAR (HXBAR) Q ENHANCEMENT

Mr. Federico Peretti[1], Dr. Seniz Küçük[1], Prof. Victor Plessky[2], Prof. Guillermo Villanueva[1]
[1]EPFL, [2]NanoRF Sàrl

G1: Materials and resonators, April 21, 2026, 10:45 - 12:15

Thin film LiNbO3 resonators are fundamental for current and next generation RF filters. In recent years, XBARs have gained a lot of interest because they can attain high frequencies and coupling, while retaining a significant Q. However, it remains a constant challenge to suppress spurious modes and to increase Q. To address this, different electrode layouts have been proposed, such as trapezoidal, and checker-shaped. However, all these solutions remain at the lay-out level, and the cross-sectional shape of the electrodes remains rectangular.
This work introduces an innovative hammer-shaped electrode XBAR resonator (HXBAR) that constitutes a departure from the classical cross-section. The proposed geometry minimizes mechanical displacement within the metal layer, which leads to a reduction of acoustic energy losses and of spurious modes. At the same time, the structure can be made thick, thus maintaining a low electrical resistance, thereby contributing to an improvement in the quality factor (Q).

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First optical frequency ratio measurement with the forbidden 1S0-3P0 clock transition in bosonic 198Hg

Dr. THOMAS LAUPRETRE[1], Dr Clara Zyksind[1], Dr Ashley Béguin[1], Dr Benjamin Pointard[1], Dr Rodolphe Le Targat[1], Dr Jérôme Lodewick[1], Dr Sébastien Bize[1]
[1]Laboratoire Temps Espace

G6: Clock comparisons, April 22, 2026, 13:30 - 15:00

We present the very first measurement of the 198Hg/87Sr optical frequency ratio via comparison between the first bosonic 198Hg optical clock and a state-of-the-art local strontium clock.

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Sub-attosecond Optical Frequency Transfer via Photonic Integrated Interferometer

Mr. Ziang Qiu[1], Mr. Zijie Zhou[1], Mr. Ming Li[1], Mr. Hanzhao Zhong[1], Dr. Liang Hu[1], Dr. Guiling Wu[1], Dr. Jianping Chen[1]
[1]Shanghai Jiao Tong University

G5: TFT in optical fibers 1, April 21, 2026, 13:30 - 15:00

We report an ultra-compact photonic integrated interferometer based on thin-film lithium niobate (TFLN) platform for two-way optical frequency transfer (TW-OFT). Through compact waveguide integration and stringent out-of-loop path matching, the proposed system effectively suppresses non-reciprocal, environment-induced phase noise, while significantly enhancing the system instability and accuracy. Over a continuous 48 hour measurement, the integrated interferometer exhibits sub-attosecond level time error and a short-term instability of 8.48×10-20 at 1 s, approaching the fundamental electrical noise limitation. Furthermore, it displays an exceptionally low sensitivity to ambient fluctuations, manifesting a phase-temperature coefficient of only 0.037 as/K, representing the best reported result to date. This work provides an effective technical pathway toward the development of miniaturized and large-scale networked optical frequency transfer systems.

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Chromatic Dispersion-Free Approach for High-Accuracy Time Synchronization in White Rabbit Networks

Dr. Jaffar Emad[1], Dr. Jochen Kronjäger[1]
[1]Physikalisch-technische Bundesanstalt

G5: White rabbit, April 23, 2026, 13:30 - 15:00

We report a chromatic dispersion (CD)-free time and frequency distribution architecture using White Rabbit technology. Figure 1 shows the schematic diagram of the proposed WR link. The core idea is employing polarization orthogonality for transmission and reception of the signals between the Grandmaster and the remote Slave at the same wavelength. Therefore, no asymmetry will be imposed by the CD; instead, a much smaller asymmetry will be introduced by polarization-mode dispersion (PMD), which is typically about 0.2 ps/√km and much lower than CD (typically 17 $ps \cdot nm^{-1} \cdot km^{-1}$) in standard single-mode fibers. The proposed approach may support large deployments of WR nodes where the calibration of each remote Slave is practically not feasible. The in-lab performance of the proposed scheme has been evaluated over different fiber link lengths, and the measurements show that the time synchronization accuracy of < 50 ps has been achieved for fiber links up to 100 km without any calibration for the CD-induced asymmetry.

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Optical frequency transfer in the presence of large Doppler shifts and rates for optical satellite links

Dr. Dominik Bourgund[1], Ludwig Blümel[1], Janis Surof[1], Manuele Dassié[1], Martin Hutterer[2], Raffaele Vitale[2], Thomas Zechel[1], Janko Janusch[2], Juraj Poliak[1]
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G5: Optical TFT in space, April 22, 2026, 10:45 - 12:15

GNSS system evolution moves towards optical technologies like optical clocks and optical inter-satellite communication. DLR's Kepler concept proposes improved robustness and precision in satellite navigation by using in-orbit ranging and synchronization achieved via optical laser communication and ranging terminals. The time transfer between different nodes is impeded by the large Doppler shifts and Doppler rates, especially for links involving low-earth orbits. Similarly, high-precision frequency transfer in the presence of Doppler shifts is very challenging and has so far only been demonstrated for moderate Doppler shifts and rates. Here, we show a concept for simultaneous two-way time transfer at the picosecond level and two-way frequency transfer at 1e-14 at 1 s gate time. Stabilities below 1e-16 at a gate time of one day evaluated via Allan deviation can be reached. These targets improve on existing RF-based technologies by a factor of at least 10, showcasing significant advantages of optical intersatellite links. Doppler shifts of several GHz as well as Doppler rates of up to 100 MHz/s are considered, covering many different inter- and intra-orbital link types for a wide range of use cases.
In the lab demonstrator, an optical free-space link is established using BPSK modulated continuous-wave lasers in the C-band. Two optical cavities serve as references for the frequency transfer. The atmospheric conditions are emulated by means of fiber-based optical intensity and phase modulators while the Doppler shift is implemented by tuning the local oscillator over the relevant frequency ranges. We detect the intradyne beat signal between the designated counter units at both the "local" and "remote" site. These counters are required to be continuous over the full frequency range of ca. 15 GHz while still maintaining phase noise significantly better than one cycle i.e. a time interval jitter <10 ps. This requires dedicated counter development included in this work. Finally, we combine the intradyne beat signals from all counter units to extract frequency transfer observables. Here, we perform functional modelling to include the effect of atmospheric delays, orbits with their corresponding orbit determination errors, relativistic corrections and hardware delays to allow for frequency transfer with corrections on the 1e-15 level for different link types.
In contrast to other common approaches, by using modulated cw-links instead of frequency combs, we are able to compensate Doppler shifts that are significantly higher than previous demonstrations, paving the road towards robust and stable inter-orbital optical links. This technology will be crucial for future developments, especially in low-earth orbit applications.

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Alternative approach to time delay interferometry with optical frequency comb

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G5: TFT in optical fibers 2, April 23, 2026, 10:45 - 12:15

Spaceborne gravitational wave observatories, exemplified by the Laser Interferometer Space Antenna (LISA) mission, are designed to remove laser noise and clock noise from interferometric phase measurements by a postprocessing technique called time-delay interferometry (TDI). For clock noise suppression, the planned observatories will utilize electro-optic modulators (EOMs) to encode the onboard clock timing onto the beam phase. Recent research has demonstrated the advantage of introducing an optical frequency comb (OFC) in the metrology system with the modified framework of TDI: the removal of the EOM and the simultaneous suppression of the stochastic jitter of the laser and the clock in the observation band. In this work, we explore an alternative approach with the OFC-based metrology system. We report that after proper treatment, it is possible to use the measured intersatellite carrier-carrier heterodyne frequencies to monitor the time derivative of the intersatellite pseudoranges, which represent the physical light travel time and the clock difference between spacecraft. This approach does not require changing the existing TDI framework, as previous OFC based efforts did. We also present the experimental demonstration of our scheme using two separate phase measurement systems to model two spacecraft. Using this novel approach, we synchronize the two independent systems with an accuracy better than 0.47 ns, while the stochastic jitter in the observation band is suppressed down to the setup sensitivity around the LISA performance levels at 15 pm/√Hz.

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Galileo Space Clocks Research and Development Programme

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G5: Microwave TFT in space, April 22, 2026, 13:30 - 15:00

This presentation provides an overview of the European Union funded ESA-led Space clocks Research and Developments portfolio for Galileo programme, with a focus on its current status and future directions. Particular emphasis is placed on the progress and prospects of alternative Space clock technologies, as well as the identification of Ground-based clock solutions intended for the future Galileo Precision Timing Facility (PTF), which is responsible for the realization of Galileo System Time (GST).

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Impact of an optical redefinition of the SI second on the international time scales TAI and TT(BIPM)

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G5+G6: Redefinition of the second, April 23, 2026, 13:30 - 15:00

Recent progress in optical frequency standards has laid the groundwork for a redefinition of the SI second based on one or multiple optical frequency atomic transitions. Optical frequency standards have evaluated uncertainties around 100 times lower than the microwave frequency caesium fountain primary standards which currently realise the definition of the second. The Consultative Committee for Time & Frequency (CCTF) has laid out several criteria which must be met before a redefinition - currently targeted for 2030. These criteria aim to ensure the maturity of the technology at the point of redefinition and to maintain consistency with the previous definition. Criterion I.4 concerns the contribution of optical frequency standards to International Atomic Time (TAI) as secondary frequency standards, placing minimum constraints on contributions from state-of-the-art optical frequency standards and requiring checks that there should be no degradation to TAI if it were calibrated by optical standards.

We have carried out the first evaluation of the impact of an optical redefinition of the second on TAI and on the BIPM's realisation of Terrestrial Time, TT(BIPM). For a single transition (Option 1) definition, each of ^{87}Sr 5s^2 $^1S_0$ – 5s5p $^3P_0$, ^{171}Yb 6s^2 $^1S_0$ – 6s6p $^3P_0$ and ^{171}Yb+ 6s ^{2}S1/2 – 4f^{13}6s^2 ^{2}F7/2 were considered in turn as the defining transition. These were selected based on availability of data from past TAI contributions. The optimised frequency values for secondary representations of the second were recalculated in each scenario, following the methodology used in recent updates to the BIPM's list of recommended frequency values. The uncertainties on these values are part of the input to the TAI and TT(BIPM) algorithms. The case of a definition based on an ensemble of transitions (Option 2) will also be considered at the conference.

Using the updated uncertainties on the recalculated optimised frequency values, we have simulated the evaluation of the frequency of TAI with respect to TT(BIPM) - referred to as 'd' in Circular T. We have compared 'd' and its uncertainty to the current definition case for each potential optical definition case, allowing us to estimate the impact of an optical definition of the second on TAI and TT(BIPM). By analysing the number of optical frequency standards contributing to TAI and TT(BIPM) in each period, their uncertainties, and therefore their weights in the algorithms, we can provide an assessment of the requirements on optical contributions to TAI to ensure there is no degradation to TAI or its uncertainty in the case of a redefinition. The result is in agreement with the relevant redefinition criterion and is an indicator of the progress needed for an optical definition of the second.

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TT(BIPM): its realization and use as a long-term reference Timescale

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G5: Timescales, April 22, 2026, 15:30 - 17:00

The BIPM computes in deferred time, every year TT(BIPM), which is based on integrating a weighted average of the evaluations of TAI frequency by the PSFS. Here we review the history of TT(BIPM) and the developments that have occurred over the last three decades concerning the realization of the timescale on one side and the uses of the timescale on the other side. We present the theoretical basis of the computation algorithm of the timescale and the details of its realization. We also explore some possible consequences of important changes that occurred in recent years with ultra-accurate PSFS and a large increase in the number of submitted PSFS evaluations.
We review the use of TT(BIPM) to estimate the performance of primary and secondary standards which measurements form the basis of the scale itself. We focus our analysis on the adaptability of the algorithm to the current situation, in which the instability of the EAL is becoming greater than that of the PSFS contributing to the TT(BIPM), a situation which is different from when the algorithm was developed.

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Balanced Grating Magneto-Optical Trap for a Miniature Cold Cesium Atomic Clock

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G3: Cold-atom deployable clocks, April 22, 2026, 10:45 - 12:15

We will report on the progress of our study of the grating magneto-optical trap (gMOT) of cesium atoms, which are directly related to the definition of the SI second, with a view to miniaturizing the apparatus of a cold atom clock. In a gMOT of cesium atoms, the radiation force away from the grating by diagonal diffraction beams is weakened due to the high nuclear spin. To compensate for the inadequate force, we have developed a new method called a balanced gMOT, which uses a grating with an aperture. In this method, a central part of the incident cooling beam that passes through the aperture is retroreflected. The cooling beams comprise the incident, retroreflected and four diagonally diffracted beams. By adjusting the intensity of the retroreflected beam, cold atoms of 7.0×10^6 were captured. The atoms were then cooled to 15 μK vertically and 45 μK parallel to the grating surface by polarization gradient cooling.

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SDR Design for Signal Processing and Code Phase Measurement of TWSTFT Signals

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G5: Free space links & timescales, April 21, 2026, 10:45 - 12:15

TWSTFT is a well-established time transfer system contributing to UTC, generally exhibiting a measurement precision better than 1 ns. TWSTFT primarily utilizes the Ku-band (12–14 GHz uplink, 10–12 GHz downlink) to exchange, measure, correct, and differentiate 1PPS-synchronized signals via a geostationary relay satellite. The Korea Research Institute of Standards and Science (KRISS) maintains TWSTFT links with other National Metrology Institutes (NMIs) for international time comparison, operating in a time-division multiplexing manner.

In this study, we introduce a Software-Defined Radio (SDR) designed for TWSTFT signal processing and code phase measurement. The designed SDR employs an FFT/IFFT-based high-speed signal acquisition algorithm. For signal tracking, it utilizes a Delay Locked Loop (DLL) discriminator based on the 0.5 chip Early-Minus-Late Power (EMLP), commonly used in GNSS processing, along with an atan2 Frequency Locked Loop (FLL) discriminator using In-phase and Quadrature correlator values. A Code Doppler-based code phase measurement algorithm was also developed to obtain precise measurements.

The SDR was evaluated using signals from the EU-ASIA link (including signals from PTB and NICT). Test results confirmed that the Total Time Deviation (TTDEV) of the second-order fitting residual for the code measurements was less than 600 ps for the averaging time in the range of 1 second and above. This achieved a measurement performance level comparable to that of commercial TWSTFT modems. This successful implementation shows the feasibility of high-precision, flexible, and robust TWSTFT processing using a designed SDR system.

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Room-temperature ultra-stable cavity with crystalline coatings enabling fractional instability near 4 × 10-17

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G6+G2: Ultrastable lasers, April 23, 2026, 08:45 - 10:15

We stabilize a 1542 nm laser to a 48 cm ULE cavity with crystalline AlGaAs coatings at 297 K and reach a record low frequency instability of 4.2×10-17 near 400 s averaging time. For averaging times between 12 s and 1000 s the instability is below the total thermal noise of 5.5×10-17 expected from a similar cavity with dielectric coatings.
To overcome low frequency tilt noise from commercial active vibration isolation systems, we correct the frequency using data from tiltmeter and seismometer. We will also present the full noise budget including a contribution from the coating birefringent noise.

Toward a Silicon Fabry–Perot Cavity with Sub-10^{-17} Stability in a Dilution Cryostat

Mr Pierre Roset[1], Mrs Yara Hariri[1], Dr Rémi Meyer[1], Dr Jacques Millo[1], Dr Clément Lacroûte[1], Prof Yann Kersalé[1], Prof. Jonathan Gillot[1]
[1]Femto-st

G6+G2: Ultrastable lasers, April 23, 2026, 08:45 - 10:15

Efforts are being made to reduce the short-term instability and frequency drift of ultra-stable lasers based on Fabry–Perot cavities (FPC)[1]. These improvements can be achieved, for instance, by operating at lower temperatures[2], using low-noise temperature controllers, using crystalline mirror coatings and employing materials with higher mechanical Q-factors. These advancements make ultra-stable cryogenic silicon cavities promising candidates for flywheel oscillators, key components in the future redefinition of the second.
We are developing an ultra-stable laser based on an 18-cm-long silicon FPC with crystalline AlGaAs/GaAs coatings, exhibiting a measured finesse of about 420,000. The FPC is currently operated at 530 mK inside a dilution cryocooler. The thermal noise of this cavity is expected to reach a relative stability of a few 10^{-18}. So far, the cavity exhibits stability in the low 10^{-16} range. To achieve sub-10^{-17} stability, all other noise sources must be reduced below this limit. In this study, we address four main noise sources.
We previously reported measurements of the coefficient of thermal expansion (CTE) of silicon at sub-kelvin temperatures[2]. At 600 mK, the CTE is approximately 10^{-13} K^{-1}, implying that a relative temperature stability of 10^{-5} K is required to make the thermal expansion contribution negligible. We achieved this with a low-noise temperature controller.
Birefringent effects arise from the crystalline mirror coatings[3]. One of the main limitations in achieving fractional frequency stability in the 10^{-17} range is spontaneous birefringent noise. To mitigate this effect, we implemented a dual-frequency locking scheme, obtaining results consistent with previous works[1,3].
Intracavity power fluctuations also pose a limitation, as they induce temperature variations in the cavity, in addition to the photo-birefringent effect present in the crystalline coatings . To address this, we implemented a transmitted-power stabilization system, reducing relative pow-er fluctuations to the 10^{-4} level.
Another limitation arises from the Doppler shift induced by cavity motion along the optical axis, due to the mechanical design of the dilution refrigerator. This effect is compensated using a heterodyne Michelson interferometer combined with a phase-locked loop.
Overall, the short-term limitation is expected to be related to vibrations from the dilution cryocooler, but in the mid-term, we expect to reach the sub-10^{-17} level. The latest results from this experiment, with all stabilization systems operational, will be presented at the conference.

1. D. Lee et al., arXiv:2509.13503, (2025).
2. P.Roset et al., arXiv:2507.13976, (2025).
3. J. Yu et al., Phys. Rev. X 13, 041002 (2023).

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Sub-picosecond Quantum Time Synchronization Over 120-km Fiber for Scalable Quantum Networks

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G5: TFT in optical fibers 2, April 23, 2026, 10:45 - 12:15

This work experimentally demonstrates a high-precision quantum time synchronization system, establishing it as a critical service for future quantum networks. The presented network architec-ture and experimental setup are shown in Fig. 1 (a), which is implemented between two inde-pendent nodes over a 120 km single-mode fiber link, utilizing a shared energy-time entangled biphoton source at 1560 nm. Based on the quantum two-way time transfer (Q-TWTT) protocol, we achieved a time deviation (TDEV) of 1.7 ps at an averaging time of 5 seconds, scaling down to 0.3 ps at 400 seconds in Fig.1 (b).
The core innovation of our architecture is the multiplexed use of the same energy-time entangled photon pairs and the quantum channel to concurrently support a second quantum protocol—dispersive optics quantum key distribution (DO-QKD). This synergistic operation not only vali-dates the quality of the synchronization but also efficiently generates secure keys, with an aver-age finite-size secure key rate (SKR) of (73.8±15.7) bps over the 10-hour measurement. Moreo-ver, by actively simulating eavesdropper-induced delays from 0 to 120 ps using a motorized var-iable optical delay line, we verified that the integrated Q-TWTT process dynamically compen-sates for these malicious perturbations, as shown in Fig.1 (c), thereby safeguarding the simulta-neous DO-QKD operation from performance degradation.
Our findings underscore the dual utility of energy-time entanglement for both metrology and cryptography, which marks a significant advancement towards practical, multi-functional quan-tum networks where high-precision timing serves as a fundamental and enabling core service.

Comparison of 176Lu+ optical frequency references having 1x10^-19 systematic uncertainty with 5.3x10^-19 precision

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G6: Ion optical clocks, April 21, 2026, 10:45 - 12:15

Accuracy assessments of optical clocks below the 10^-18 fractional uncertainty level demonstrate significant advances in controlling various systematic shifts. However, there have been relatively few comparisons between clocks to justify performance claims at even the mid 10^-18 level, which are vital to demonstrating reproducibility and providing confidence for applications such as relativistic geodesy or tests of fundamental physics.

The 176Lu+ 1S0-3D1 optical frequency standard is insensitive to electromagnetic shifts to the extent that it can readily achieve uncertainties below 10^-18 when operated at room temperature without thermal or magnetic shielding. Recent advancements in the assessment of systematic uncertainties have allowed us to construct two single-ion optical references each with a fractional frequency uncertainty near 1 x 10^-19, which is several times more accurate than the best reported references to date.

We support this accuracy claim by performing a direct comparison of the references via correlation spectroscopy, achieving frequency agreement of [-2.4 ± (5.3) stat ± (1.0) sys] x 10^-19 where ‘stat’ and ‘sys’ indicate the statistical and systematic uncertainties respectively. This is the first report to demonstrate agreement of frequency standards with a systematic uncertainty budget below 10^-18.

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ELT: An optical time transfer method using laser pulses

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G5: Optical TFT in space, April 22, 2026, 10:45 - 12:15

The Atomic Clock Ensemble in Space (ACES) was launched to the International Space Station (ISS) on 21st of April of this year. Following successful installation on the external payload facility of the Colum-bus module, the commissioning phase began, which will approximately last until the end of 2025. ACES brought two time transfer methods into orbit: the Microwave Link (MWL) and the European Laser Tim-ing (ELT) link. These two links differ not only in frequency – one operates in the microwave domain, the other in the optical domain – but also in their detection principle. In this contribution, we introduce the optical pulsed time transfer experiment ELT and compare its measurement principle with that of MWL.

ELT is a combination of Satellite Laser Ranging (SLR), a round trip time of flight measurement of laser pulses to determine the distance between the ground station and the satellite, and a one-way ranging technique, in which the laser pulses are time tagged in the ACES timescale. Although the entire SLR ground segment is available in principle, restrictions exist for ranging to the ISS and the availability of a stable clock signal at these geodetic stations.

The Wettzell Laser Ranging System (WLRS) located at the Geodetic Observatory Wettzell in Germany is the main ground station for the ELT experiment. We describe the steps taken at WLRS to participate in the ELT experiment and the available hardware. We then present the ACES payload and the ELT Data Center, which is responsible for the data processing chain. We highlight the challenges of the data pro-cessing based on the first synchronisation measurements between Wettzell and the ACES time scale. Finally, we discuss the objectives of ELT.

Passive TWSTFT: A cost-effective alternative for robust UTC(k) dissemination

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G5: Satellite based TFT, April 23, 2026, 08:45 - 10:15

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is a well-established technique for high-accuracy clock comparisons, relying on the exchange of bidirectional timing signals via geostationary satellites. This active configuration requires both transmit and receive capabilities, which limits its scalability due to cost, equipment complexity, and satellite bandwidth constraints. To address this, passive TWSTFT has been proposed, wherein receive-only users synchronize to UTC(k) by calibrating single-way pseudoranging observables for both static equipment delays and dynamic effects such as satellite motion and atmospheric propagation.

This work targets an end-to-end implementation of passive TWSTFT, from system conceptualization through field deployment and validation. A 120-day dataset from the active TWSTFT network was processed using precise orbit determination to estimate the satellite ephemeris and system delays. A low-cost passive terminal—based on a commercial TV antenna and software-defined radio—was calibrated in common-clock mode at INRIM and deployed to the Côte d'Azur Observatory (OCA) for field validation. Time transfer with five European UTC(k) laboratories was achieved over a 40-day period, showing agreement within 1–2 ns against independent GNSS and active TWSTFT links. A preliminary uncertainty analysis, based on the stability of the calibration before and after field deployment, and on the consistency of passive TWSTFT results with independent techniques, suggests a standard uncertainty on the order of 5 ns (1σ).

This offers a scalable, cost-effective, and interference-resilient alternative to GNSS for secure time distribution. Future work will focus on automating OD processes for enabling real-time ephemeris updates to support wider adoption of passive TWSTFT in metrology, critical infrastructure, and scientific applications.

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Picosecond-Range White Rabbit Digital Time Scale

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G5: White rabbit, April 23, 2026, 13:30 - 15:00

Time and frequency distribution through White Rabbit (WR) Ethernet allows synchronization of network nodes with residual offsets of the order of 100 ps relative to a reference clock. This per-formance places WR in a position to back up or complement clock synchronization via global navigation satellite system (GNSS) receivers, and thereby mitigate the risks of GNSS outage. The accuracy of WR also makes it suitable for technologies that require deep sub-nanosecond synchronization, such as quantum networks and enhanced terrestrial positioning.

By design, WR tracks a single reference clock, which introduces a single point of failure in a network that – in principle – holds great promise for resilience. Fortunately, the networked, multibranch character of WR and its software-based implementation make it possible to intro-duce back-up reference clocks to a WR network so that if the primary reference clock fails, the network can fail over to one of the back-up clocks. However, this introduces the challenge of the typical nanoseconds-to-microseconds time differences between different atomic clocks, meaning that a fail-over event will cause a many-nanosecond discontinuity in the sub-nanosecond WR network. In addition, such an arrangement of back-up reference clocks also leaves the time and frequency stability of the back-up clocks unused.

Here, we present a WR digital time scale that solves the above issues in an all-digital way. Our solution starts out from a number of free-running atomic reference clocks (in our case an ensem-ble of two Rb and two Cs clocks), each of which synchronizes a WR grandmaster (GM) switch. The GM switches connect to a WR comparator switch with modified WR software that enables the comparison of the WR GM time offsets. The GM time offsets are transferred via the network to a server running a time-scale software algorithm, which subsequently computes offsets of each GM (and thereby of each reference clock) relative to the digital time scale (the latter being anal-ogous to a paper time scale). The clock offsets are subsequently transmitted via the network, where WR switches (in our case the comparator switch) can use these offsets to correct their WR PTP clock via adjustment of the WR SoftPLL setpoint, thus realizing the digital time scale.

We implemented our four-clock WR digital time scale in a testbed that includes a 24-km metropolitan fiber link, and a 110-km link to UTC(VSL) via the SURF Time&Frequency Network for validation. Two independent time-scale realizations, steered by independent time-scale algorithms, illustrate the robustness of the time scale, which has no single point of failure. The time-scale algorithm ensures close-to-optimum frequency stability, taking advantage of the combined stability of the atomic clocks, and the two time-scale realizations display residual offsets of about 100 ps or less. These results point to the possibility of resilient, all-digital picosecond-range net-work time scales that may be implemented in existing wide-area fiber-optic infrastructure.

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Yb/Sr optical frequency ratio with a transportable clock

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G6: Clock comparisons, April 22, 2026, 13:30 - 15:00

Optical clock comparisons are key to validating frequency standards, but achieving consistency at the 10^{-18} level remains challenging, particularly for remote comparisons where relativistic effects must be carefully accounted for. Transportable clocks help address these challenges by enabling precise local frequency ratio measurements.

In March - April 2025, a local comparison was carried out at INRIM between its ytterbium lattice clock IT-Yb1 and PTB's transportable strontium clock PTB-Sr4. The superior stability of the PTB-Sr4 clock laser was transferred to the Yb system, improving its stability fourfold, from $2\times10^{-15}(\tau/s)^{-1/2}$ to $5\times10^{-16}(\tau/s)^{-1/2}$. The campaign produced 144 hours of common uptime and yielded a frequency ratio ν_Yb / ν_Sr = 1.207 507 039 343 337 726(25), with the uncertainty dominated by the 2.0×10^{-17} systematic uncertainty of IT-Yb1.

This result contributes to a broader European effort to refine optical frequency ratios and supports progress toward redefining the SI second.

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Frequency-Combs for Optical Clocks in Space

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G6: Optical frequency combs, April 22, 2026, 10:45 - 12:15

We present a low SWaP, radiation-tolerant and vacuum compatible space frequency comb designed for next-generation space optical clocks. Our system has been developed in anticipation of upcoming DLR and ESA missions like COMPASSO, GIC and CRONOS. It has been successfully adapted to different payload bays, cooling concepts and various optical, rf and communication interfaces, including ESA's packet utilization service (PUS), ensuring versatile integration.
Frequency combs are at the heart of quantum sensors and optical clocks, enabling reference and control of continuous-wave (cw) laser systems and facilitating the transfer of optical frequencies within the optical domain or to the RF domain with accuracy and stability beyond 1E16. In a qualifying comb-comb comparison we have demonstrated a MADEV of 4.5×1E-16 @1s averaging down to 5.1×1E-17 @100s within the optical domain. Our advanced internal architecture enables the comb to achieve its outstanding performance under vacuum and zero-gravity conditions on free-flying or space station platforms.
All optical and EEE (Electrical, Electronic, and Electromechanical) components have been se-lected and/or qualified for MEO radiation environments. Flight systems are qualified to meet mission environment requirements, encompassing shock, vibration, thermal cycling, thermal vac-uum, and electromagnetic compatibility (EMC) testing. The design standard mandates compre-hensive finite element method (FEM) analyses for both mechanical and thermal aspects prior to manufacturing, ensuring rigorous validation and reliability.
Beyond their critical role in high-performance optical clock operation, frequency combs can also support the long-distance dissemination of time and frequency information via bidirectional comb-referenced laser links, as well as inter-satellite precision ranging. Future applications of space frequency combs include GNSS, Earth observation, gravity missions, ranging, calibration of spectrometers in space observatories, and supporting missions exploring fundamental physics based on precision clocks and timing.

Development of a 5-liter iodine optical atomic clock

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G6: Commercial optical clocks, April 23, 2026, 08:45 - 10:15

We present the development of a 5-liter iodine optical atomic clock. Volume was reduced by co-integrating electronics with redesigned packages for the core physics subsystems. The result is a footprint compatible with space deployment. The clock consumes 40 Watts of power, includes outputs at 10 MHz, 100 MHz, and 1 PPS, and exhibits an instability of 5e-14 / root(tau). Frequency stability, phase noise, power consumption, and operating temperature range for a fully integrated prototype will be presented.

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High-pulse-energy integrated mode-locked lasers enabling on-chip supercontinuum generation

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G6: Optical frequency combs, April 22, 2026, 10:45 - 12:15

A fully integrated frequency comb featuring an octave-spanning spectrum and an electronically detectable repetition rate has long been sought for its potential to enable chip-scale optical atomic clocks and low-noise microwave generation via optical frequency division. Here, we demonstrate the first wafer-scale fabricated photonic integrated ultrafast mode-locked laser capable of generating pulses with energies exceeding 1 nJ on-chip, as well as generating a octave spanning supercontinuum in another waveguide directly. We believe this may open a new path for an integrated self-referenced frequency comb for timing applications.

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Cryptographically Secured High-Performance Time Synchronization for Long-Distance White Rabbit Links

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G5: White rabbit, April 23, 2026, 13:30 - 15:00

The requirements for time synchronization in communication networks have become increasingly stringent. Applications such as power distribution and telecommunications demand accuracies which can be as tight as 100 ns. GNSS-based methods can achieve this but are susceptible to jamming and spoofing. Wired solutions like the Precision Time Protocol (PTP), White Rabbit (WR), or ELSTAB also show vulnerabilities to attacks. With the initiative of IEEE P1588k and IETF, a standard that specifies security mechanisms is currently being developed for PTP. This paper describes the development of a WR-based demonstrator that integrates and implements the draft security standard, enabling cryptographically secured time synchronization over optical fibre without loss of precision or accuracy.

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Multi-ion optical clock with 173Yb+

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G6: Advanced optical clocks, April 21, 2026, 13:30 - 15:00

The Yb ion has an extremely narrow transition and high sensitivity to several properties of fundamental physics. Operating with multiple ions could further improve sensitivity and shorten measurement time. However, due to the strong AC Stark shift induced by the clock laser, operating with multiple ions remains a challenge for Yb ions.
This problem could potentially be overcome by using 173Yb+, which is expected to exhibit a much smaller AC Stark shift due to nuclear quenching. We present the latest results of 173Yb+ spectroscopy and demonstrate the predicted nuclear spin-induced quenching effect, which leads to a shortened lifetime of the electric octupole clock transition. We also discuss the implications of 173Yb+ for future multi-ion clocks.

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Pulsed Frequency-Doubled Laser System for Rb Atomic Frequency Standards

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G3: Vapor-cell deployable clocks, April 23, 2026, 13:30 - 15:00

Frequency-stabilized laser sources featuring low intensity and frequency noise as well as high reliability are key requirements for the realization of any type of modern atomic frequency standards, and such is true also for Rb atomic frequency standards.
Here we report on the realization and experimental evaluation of a pulsed and frequency-stabilized laser system for Rb-cell Pulsed Optically Pumped (POP) clocks. The system is largely based on telecom-grade fiber-coupled components at 1560 nm, whose light is then frequency-doubled to meet the Rb D2 line at 780 nm. 1560 nm light from a 1 MHz linewidth fiber-coupled DFB laser is amplified in an Erbium-Doped Fiber Amplifier (EDFA) and split into two branches. In the first branch, the light is frequency-doubled in a Second Harmonic Generation (SHG) module and then sent to a Frequency Reference Unit (FRU) with a compact saturated-absorption spectroscopy setup for frequency stabilization in continuous-wave mode. In the second branch, light pulses are created at 1560 nm using a fiber-coupled Acousto-Optical Modulator (AOM) followed by SHG. The light extinction ratio of the 780 nm output thus benefits from the quadratic power behavior of the SHG and is measured at ≥ 75 dB.
In comparison to our previous standard 780 nm laser systems, optical power available is increased by a factor of 2, extinction ratio is improved by 40 dB, and RIN at 100 Hz and frequency noise show comparable levels. The implementation of the laser system in an atomic clock setup is currently on-going.

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Development of an additively manufactured compact cold-atom fountain clock

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G3: Cold-atom deployable clocks, April 22, 2026, 10:45 - 12:15

Here we present recent progress toward developing a compact cold-atom microwave fountain clock based on a grating MOT (gMOT) and an additively-manufactured microwave cavity. These components aim to simplify the overall system complexity and bring the design closer to a mass-producible clock. We discuss the clock's design and preliminary performance and highlight recent improvements intended to enhance both short-term and long-term stability.

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Establishing infrastructure for NICT's optical frequency distribution

Dr. Nils Nemitz[1], Dr. Miho Fujieda[1], Dr. Mads Tønnes[1], Dr. Motohiro Kumagai[1], Dr. Tetsuya Ido[1]
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G5: TFT in optical fibers 1, April 21, 2026, 13:30 - 15:00

NICT has engaged in the development of fiber frequency links since early comparison campaigns of its optical lattice clock and maintains an RF-over-fiber link to provide a reliable reference frequency to equipment at the University of Tokyo.

As optical clocks become robust enough for sustained and regular operation, we are renewing our effort to develop an infrastructure for the continuous distribution of an optical reference. Outside of timekeeping and precision metrology, this also benefits applications like quantum key distribution.

We will show results for a cascaded 300 km link that is undergoing laboratory tests. The system is designed to operate with a compact rack-mounted repeater station with remote monitoring and control. A core element is a newly developed digital fiber noise cancellation system, tracking and recording the large, multicycle phase excursions of a long-distance fiber link, while applying corrections with a bandwidth and baseline frequency that can be digitally configured. Recorded data and real-time plots provide diagnostics for the link without additional instrumentation.

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Coherent Laser Interferometry for Distributed Sensing and Event Localization

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G5: TFT in optical fibers 2, April 23, 2026, 10:45 - 12:15

Coherent laser interferometry on optical fibers has emerged as a promising tool for distributed fiber sensing. Unlike more conventional approaches, it is fully compliant with the present architecture of global communications, potentially enabling wide scale adoption and application to critical tasks such as seismic surveillance, environmental monitoring and infrastructures supervision. Achieving these important goals requires addressing critical challenges: laser interferometry does not enable locating disturbances, as it only provides a measure of the integrated cable deformation. Moreover, the size, weight, and power consumption of present interrogator systems, based on ultrastable lasers, is not suitable for device integration and large-scale production.
We developed a two-way interrogation scheme that enables event localization along the fiber, based on a pair of counterpropagating laser beams and acquisitions at opposite cable ends syn-chronized at better than 10 µs4. By cross-correlating collected datasets (Fig. 1), we localized events with uncertainty <1 km, mostly depending on the event spectral content and signal/noise ratio. Our analysis was conducted in field-deployed cables, where we could successfully pin-point roadworks and vehicle passages close to the cable. These results are encouraging in view of developing cable safety supervision and damage prevention systems.
Additionally, we have implemented low-noise homodyne phase-detection strategies that do not require RF optoelectronics and balance performances with affordability and suitability for pho-tonic integration. This approach is particularly attracting for short-range interferometry-based sensing systems that do not require ultrastable lasers. Thanks to its low cost and power consumption and high potential for chip-scale integration, it can be applied to the metropolitan context for infrastructural health monitoring.

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Memristor-like Resonant MEMS Accelerometer

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G4: Micro and nano resonant sensors, April 22, 2026, 15:30 - 17:00

We present, for the first time, the observation of cross-domain pinched hysteresis in the amplitude-stiffness response of a resonant MEMS accelerometer. Pinched hysteresis is the hallmark characteristic of a memristor, a key building block for in-sensor computation systems and energy-efficient edge AI. Unlike memristors, which have an electrical domain input and output, the pinched hysteresis within the resonant MEMS accelerometer has a physical domain input and an electrical domain output, demonstrating that resonant MEMS sensors can be utilized for in-sensor computing devices, offering sensor-integrated sensing, memory, and computing capabilities.

Oscillator ensemble for phase noise comparison

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G2: Phase-frequency comparisons and analysis, April 23, 2026, 10:45 - 12:15

An international comparison of oscillator phase noise is in progress [1] led by the French LNE (service provided by FEMTO-ST). The comparison starts as an EURAMET initiative, thus addressed to the European labs of primary metrology, but it is widely open to qualified labs. Until now, 21 labs joined the initiative: 11 EURAMET NMIs/DIs, 1 non-EURAMET NMI, 1 European gov lab, and 8 industries in Europe.
Two phase noise comparisons were done before at significant smaller scale (national or bilateral), circulating frequency synthesizers [2]. In contrast, oscillators challenge the instruments because of their lower noise and strange output impedance. Virtually all instruments make use of correlation between two independent channels which measure simultaneously the oscillator under test. The instruments are prone to crosstalk, the thermal energy in the input power splitter is generally not accounted for, and the generalized use of the absolute value |S_yx(f)| of the cross spectrum, instead if Re{S_yx(f)}, make it impossible to detect negative, nonsensical values if they occur. Inconsistencies and gross errors have been reported by FEMTO-ST and by NIST [3].
We started with the design of an ensemble of oscillators. Each one has its own dc/dc power supply, external filters, two cascaded linear regulators, and floating ground. The dc/dc converters provide 5 kV isolation, 20 pF input-to-output. Each oscillator represents a class of widely used oscillators:
• 10 MHz OCXO, low noise and stability ≈2E–13. Similar oscillators are found as the frequency reference in high-end instruments (frequency synthesizers, network analyzers, etc.).
• 100 MHz OCXO, intended for ultra-low noise applications (telecom, frequency multiplication)
• 1 GHz SAW, represents the low-noise oscillators for high-speed digital boards. Such oscillators are also useful as an intermediate stage in frequency multiplication.
• 10 GHz DRO, typically used as a low-noise reference for most microwave applications, optionally steered to an external reference.
The ensemble of oscillators has been sent to PTB for alpha test, re-checked at FEMTO-ST, and sent out for a beta-test roundtrip (two labs) in view of regular roundtrips of 4 labs each, planned for mid-February and on. At the conference we report on the design and implementation of the ensemble of oscillators, and on the results of the alpha test at PTB.

[1] Pilot Study: Comparison of Phase Noise Measurements, EURAMET reg.no. 1589, https://www.euramet.org/technical-committees/tc-projects/details/project/comparison-of-phase-noise-measurements-pilot-study.
[2] B. Caswell, Cal Lab Magazine 21(3) pp.31-35, Jul-Aug 2014. A. Gedik et al., Bilateral Phase Noise Comparison between Tubitak UME and SASO NMCC, Proc 2019 PTTI.
[3] C. W. Nelson et al., Rev Sci Instrum 85(3), March 2014. Y. Gruson et al., Metrologia 57(5), October 2020.

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Transportable 171Yb Lattice Clock for Metrology and Geodesy

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G6: Deployable optical clocks, April 22, 2026, 15:30 - 17:00

Optical lattice clocks (OLCs) are among the best clocks in the world, offering fractional systematic uncertainties below the 1×10-18 level and able to average into the low 10-18 decade in under an hour. Fielding this level of performance in a transportable OLC is crucial for intercontinental optical frequency comparisons required for the redefinition of the second and enables direct measurements of the geopotential difference between two sites via the relativistic redshift of the clock frequency (relativistic geodesy).
We have developed a transportable 171Yb OLC targeting these metrological goals. Our system consists of four 19-inch racks: two for controllers, lasers, and the atomic physics package; one for the cavity stabilized clock local oscillator; and one for our optical clockwork comb. We expect total systematic uncertainty of 4.1×10-18, with leading uncertainty contributions from lattice Stark shift (3.5×10-18) and blackbody radiation (1.7×10-18).
Uncertainty budgets are necessary for high performance clocks, but true out-of-loop validation of clock performance requires rigorous comparison. To this end, we have moved the transportable clock (NIST-YbT) to the nearby University of Colorado Boulder campus and compared to the stationary clock at NIST (NIST-YbI) over ~3 km of fiber. We have also deployed NIST-YbT to the observatory atop Mt Blue Sky (~4300 m elevation) for a preliminary remote systems test, set-ting the stage for a future relativistic geodesy campaign via comparison to NIST-YbI using a combination of free-space and fiber time transfer.

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Free-space optical-frequency comparison between moving optical clocks

Dr Sabrina Slimani[1], Dr Ashby Hilton[2], Dr Benjamin Dix-Matthews[1], Dr Nicolas Bourbeau Hebert[2], Ms Lilani Toms-Hardman[1], Dr Sarah Watzdorf[2], Mr Ayden McCann[1], Dr Elizaveta Klantsataya[2], Mr Christopher Billington[2], Mr Aidan Strathern[2], Prof. Andre Luiten[3], Prof. Sascha Schediwy[1]
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G5: Free space links & timescales, April 21, 2026, 10:45 - 12:15

Portable optical-frequency atomic clocks have reached a maturity level that allows them to be used outside of a laboratory setting. Specifically, portable optical clocks have been demonstrated in sea trials [1], in urban deployments [2], and clock sub-systems have even been operated on-orbit [3]. Portable optical clocks will be integral in advancing fundamental physics including tests of General Relativity; conducting novel geoscience using chronometric geodesy; enhancing national security through secure remote synchronization; and likely form the backbone of next-generation global navigation satellite systems [4].

Portable optical clocks will be integral in advancing fundamental physics including tests of General Relativity; conducting novel geoscience using chronometric geodesy; enhancing national security through secure remote synchronization; and likely form the backbone of next-generation global navigation satellite systems [5]. However, many of the above-mentioned applications require timescale comparison with a precision better than the stability of the clocks. Where this involves moving optical clocks, this can only be achieved using Doppler-compensated free-space optical frequency transfer [6].

Here we report on timescale comparison over a point-to-point, free-space link between a stationary optical clock and one carried on a moving platform. The two portable optical clocks used for this work are capable of achieving stabilities of 1.5e−14 per $\sqrt{\tau}$, reaching 3e−15 at 100 s of integration [1]. This is accomplished in a 25 kg, 3 U package, with 100 W power draw. The optical-frequency transfer system (1U package) has a stability of 4e−18 at 1 s and 4e−18 at 100 s, as demonstrated over a 2.4 km free-space link [7]. The active optical terminals used in this work have a mass of 4.7 kg, a 10.9 L volume, and a 43 W power draw. All systems are portable and field-deployable in additional novel scenarios.

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High up-time calibrations of TAI with a Sr optical lattice clock

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G6: Optical clocks metrology, April 23, 2026, 10:45 - 12:15

In this paper, we report on the operation of the LNE-OP SrB Sr optical lattice clock since April 2025, resulting, at the time of writing into more than 7 consecutive months of calibrations included in the BIPM Circular T. All these calibrations have an uncertainty lower than the 2×10-16 mark, which constitutes a significant progress in completing the roadmap towards the redefinition of the SI second.

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Real-time measurement of the tidally induced geopotential changes via optical clocks

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G6: Deployable optical clocks, April 22, 2026, 15:30 - 17:00

Optical lattice clocks offer the lowest instabilities of any existing frequency standards, reaching σy < 1×10−16 (τ/s)−1/2. This enables fast frequency comparisons reaching 1×10−18 uncertainty within few hours. Optical interferometric fibre links enable such comparisons across continents with no loss of stability for these averaging times, allowing the comparison of lattice clocks at remote locations and the observation of variations of geopotential differences in real time.
We report on comparisons of various stationary and transportable lattice clocks across four in-stitutes in Europe, involving PTB, INRiM, LTE and NPL during the year 2025. In particular, the PTB transportable clock Sr4 was operated at INRiM in Torino, Italy and compared to the sta-tionary clock Sr3 at PTB in Brunswick, Germany over a period of several days in March of 2025. The observed frequency ratio clearly resolves the variation of the geopotential difference, which is caused mainly by tides. We compare this and other measurements to the predictions from tide models. These demonstrations show that international clock comparisons have reached a level of stability where time-dependent variations can not only be resolved but need to be considered during data analysis, e.g., aliasing induced by interruptions in the operation of the clocks or links at similar time scales.

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Visualizing the Ensemble Second

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G5+G6: Redefinition of the second, April 23, 2026, 13:30 - 15:00

To apply optical clocks to precise timekeeping, the Roadmap to the Redefinition of the SI Second aims to replace the current definition in 2030.

Option 1 for this redefinition is to continue with one specific optical transition in place of cesium's microwave transition. This is easy to communicate and provides a clear path to obtaining a primary realization of the second.

Option 2 aims for greater accuracy by fixing a mean value instead. However, it remains challenging to visualize and to communicate how multiple optical transitions can be integrated to form a singular definition with no contradictions.

We illustrate Option 2 as creating normalized frequencies for each transition that all approximate 1Hz to the full accuracy of current measurements. Their weighted arithmetic mean is the best continuation of the cesium-defined 1Hz frequency that the optical ensemble can provide, and fixing this single mean value to be 1 Hz then unambiguously defines the optical SI second. While this is a reformulation of the original proposal, it is mathematically equivalent.

The defined normalizing constants do not fix the numerical values of the transition frequencies, such that even a perfect realization still has a residual deviation from 1Hz. We visualize this as a constellation of residuals, permanently set with the new definition, that defines the ensemble second by its barycenter. This barycenter is accessible from any point of the constellation.

The BIPM Working Group on Frequency Standards already collects the needed information, and we find that the published recommended frequencies for secondary representations of the second, combined with the covariance matrix of their uncertainties, efficiently communicate the information required to explore the available options for the redefinition and the resulting uncertainties without reevaluating the source data of reported frequency ratios.

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Monitoring of Galileo Broadcast Group Delays

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G5: Satellite based TFT, April 23, 2026, 08:45 - 10:15

Group delays refer to the hardware delays originating from the analogue and digital parts of both a satellite's transmission and the station's reception equipment. These signal delays must be considered when dealing with GNSS code pseudorange-based positioning and timing applications using a signal or combination of signals that differ from those employed in the generation of satellite clock products. In their navigation messages, Galileo satellites provide clock offsets based on a dual-frequency ionosphere-free combination, and transmit broadcast group delay (BGD) parameters for use in single-frequency navigation. These are BGD(E1, E5a), transmitted on the FNAV navigation message, and BGD(E1, E5b) transmitted on the INAV message.

Based on EU Member States existing facilities, the Galileo and EGNOS Monitoring Of Performances consortium (GEMOP) provides EUSPA with means for independent monitoring and assessment of the GNSS services, more in particular of Galileo. The GEMOP consortium is composed of 27 partners from 15 EU Member States plus Norway and has been awarded by EUSPA a 7-year framework partnership agreement. For this project, Galileo BGD accuracy (i.e. the difference between the broadcast value and the measured one) is monitored. The accuracy of BGDs is important because it directly impacts the precision of positioning and timing solutions obtained using single-frequency receivers.

At the Royal Observatory of Belgium, Galileo BGDs are computed from the pseudorange measurements collected by the BRUX (Brussels) GNSS station, fully calibrated as in the scheme of UTC(k) station calibrations. The ionospheric delays are furthermore removed using maps of Total Electron Content (TEC) provided by the International GNSS Service (IGS). The BGD accuracy is determined for both BGD(E1, E5a) and BGD(E1, E5b). This comparison provides an absolute determination of BGD values. At CNES, the Navigation and Time Monitoring Facility (NTMF) monitors the BGD accuracy comparing the consolidated broadcast values with Differential Code Biases (DCB) determined by the Chinese Academy of Sciences (CAS) analysis center in Wuhan. A similar approach is performed at NMA. As the DCB CAS products are not calibrated, they only provide relative monitoring of the BGDs, i.e. stability and inter-satellite biases.

We present the results of the Galileo FNAV and INAV BGD accuracy monitoring activity over the past few years, focusing on specific interesting events. From this analysis, we conclude that the current BGD accuracy is at a few ns level, with important variations in some periods, limiting at the same level the accuracy of Galileo single-frequency timing solutions and therefore the positioning errors. A comparison with BGD accuracies for GPS, GLONASS and BDS-3 is also presented.

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Establishment of Phase Noise Traceability to SI Units in PTB

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G2: Phase-frequency comparisons and analysis, April 23, 2026, 10:45 - 12:15

Phase noise, the random fluctuation of a signal's phase relative to an ideal oscillator, is a key performance metric in high-precision frequency sources. Its accurate measurement is vital for scientific, communications, and timekeeping applications. Despite previous national and inter-national efforts for phase-noise traceability, reliably extending these techniques into the ex-tremely low-noise regime required by state-of-the-art oscillators remains a challenge. At PTB, a traceable measurement capability for phase noise is being established, linking the quantity directly to the SI units of power and time through the chain of calibration.
The phase noise reference is realized by combining a low-phase-noise carrier oscillator with a calibrated broadband noise source to synthesize well-defined noise levels at carrier frequencies of 10 MHz, 100 MHz, and 1 GHz. The absolute carrier power and the spectral noise density are traced back to RF primary quantities using frequency-selective methods verified by thermal power standards traceable to the watt. On the other hand, the carrier frequency is referenced to the SI second. In addition, all RF components such as combiners, step attenuators, and cables are fully characterized by traceable S-parameter measurements, allowing corrections for sys-tematic losses and impedance mismatches.
An uncertainty budget study compliant with the BIPM GUM framework is also being devel-oped at different offset frequencies of the carriers. The output of the reference is further used to characterise and calibrate phase noise analysers, which will serve as the basis for future cali-bration services. This system thus establishes an unbroken traceability chain from SI units to the measured phase noise and forms the foundation for future calibration services, inter-laboratory comparisons, and the development of next-generation metrological standards in fre-quency and time metrology.

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Lattice light-shift model errors in optical lattice clocks

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G6: Advanced optical clocks, April 21, 2026, 13:30 - 15:00

Optical lattice clocks (OLCs), known for their high precision, utilize "magic wavelength" light to confine atoms, mitigating Doppler and recoil shift while introducing light shifts that require careful evaluation. Accurately characterizing the atomic distribution within the trap, which affects the effective trap depth, is crucial for correcting these shifts. The authors propose novel approaches to measure effective trap depths and minimize model assumptions. We additionally provide a brief status update on single and multi-species clock comparisons with Yb lattice clocks performed in Boulder.

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The most suitable standard and the right moment for a redefinition: a historical perspective

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G5+G6: Redefinition of the second, April 23, 2026, 13:30 - 15:00

When the second was redefined in 1967, all three main candidates (cesium atomic beam, thallium atomic beam and hydrogen maser) were deemed to have "the same advantages as the basis for a new definition of the second", but cesium was "the most suitable (convenable) for immediate selection". The cesium beam was seen as such because it was already widely available through commercial devices, it had been most extensively replicated, compared, and validated through long-term observations, and its frequency was already used as a de-facto standard. Not to mention that only the frequency of cesium had been determined in terms of the ephemeris second, which was at that time the SI second.
Throughout its meetings in the 1950s and 1960s, the Consultative Committee for the Definition of the Second (CCDS) hoped to decide whether the time had come to redefine the second once one standard demonstrably outperformed the others in terms of stability and uncertainty. If no such standard emerged, advocates of an immediate redefinition risked further opposition from those who preferred to postpone the decision until a single candidate could be shown to surpass its rivals. To justify the immediate adoption of cesium, its advocates therefore invoked a set of pragmatic considerations that had not been previously discussed by the CCDS. This raises the question of whether the 1967 definition was adopted chiefly on this basis, or whether, once the decision to redefine had been taken for different reasons (such as the perceived urgent need for a more precise standard of time and frequency), cesium simply emerged as the only realistic option at that moment.
The history of the 1967 redefinition offers a valuable lesson for current discussions because it shows the challenge in connecting the two main questions: which standard to adopt and whether it is the right moment to redefine the second at all. In 1967, the choice of cesium was ultimately eased by the fact that no alternative clearly outperformed it in any respect. In a future redefinition, however, one might be less fortunate and face several standards that are each superior only in certain respects, but not across the board, making it even harder to single out a single winner on purely technical grounds. One might again have to decide on pragmatic grounds which standard is the most suitable.

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Evaluation of Light Shift and AOM Chirp Effect in a Ca+ Optical Clock

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G6: Optical clocks metrology, April 23, 2026, 10:45 - 12:15

Here we report the evaluation of our liquid-nitrogen-cooled Ca+ optical clock. After the blackbody radiation shift and 2nd order Doppler shift evaluated, which has been reported in EFTF 2025, there are shifts like light shift and AOM chirp effect that still need to be evaluated. Here we present the evaluation of shifts including the light shift, the AOM chirp effect, the quadratic Zeeman shift, and the collisional shift. With all the shifts taken into account, the total systematic uncertainty of the Ca+ optical clock is now evaluated as 4.6E-19. This work establishes the Ca+ ion as a competitive candidate for optical clocks at the E-19 level systematic uncertainty.
The quadratic Zeeman shift was precisely controlled following an accurate determination of the Zeeman coefficient. Furthermore, the clock-laser-induced AC Stark shift and the AOM chirp effect—were suppressed to below 1E-19 using hyper-Ramsey spectroscopy and a phase-characterized laser control system, respectively. Theoretical analysis, numerical simulations, and experiments have confirmed that the frequency-modulated hyper-Ramsey (HRS) sequence dramatically reduces the sensitivity to the AC Stark shift compared with the standard Ramsey scheme. Experimentally, clock comparison between two clock-laser power levels allows determining the AC Stark shifts of < 5E-21 under HRS method. On the other hand, AOM switching can introduce transient phase excursions (chirp), producing a frequency offset. We derived the phase-sensitivity function of the HRS sequence and found that the frequency-modulation protocol provides intrinsic cancellation of repeatable phase excursions among the four π/2 pulses. To quantify this effect, we constructed a homodyne interferometer to measure the phase trajectories of all pulses in the sequence. The averaged phase profiles show excellent reproducibility between pulses. Integrating the measured phase data with the sensitivity function yields an AOM-chirp-induced frequency shift of 1E-19.

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Frequency and Time Transfer with ESA's Genesis Satellite

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G5: Microwave TFT in space, April 22, 2026, 13:30 - 15:00

ESA is preparing for a new satellite mission called Genesis. It is a co-location satellite in a 6000 km orbit that will connect the four major space geodetic techniques on one platform in space, i.e. (a) Very Long Baseline Interferometry (VLBI), (b) Global Navigation Satellite Systems (GNSS), (c) Satellite Laser Ranging (SLR), and (d) Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS). The goal is to improve and strengthen the precision and accuracy of the International Terrestrial Reference Frame (ITRF). Genesis will fly a payload with equipment for all four techniques, i.e. receivers for GNSS, retroreflectors for SLR, a receiver for DORIS, and an active VLBI transmitter that will send signals to be observed with ground-based radio telescopes for VLBI. The aim is to be compatible with the modern VLBI Global Observing System (VGOS). VGOS is a dual-linear polarized broadband VLBI system employing 13m-class fast-slewing radio telescopes and includes today about 20 stations worldwide. While usually faint natural radio sources at cosmological distances are observed with VGOS, the VGOS telescopes also can track satellites and observe satellite signals. Genesis will use four frequency bands that are designated by ITU for space-to-earth communication, i.e. 3.1–3.3, 5.25–5.57, 8.0–8.4, and 9.3–9.8 GHz. During normal use, Genesis will send a weak white noise signal in these four frequency bands that can be received with the VGOS network and processed as standard VLBI observations. The usual interferometric processing of the VLBI data determines the relative clock difference between ground stations, thus allowing for frequency transfer on global scale. Since the four Genesis bands are rather wide, additionally pseudo-random-noise (PRN) signals could be used for one-way-ranging measurements to the satellite. As an example, reception of a 310 MHz wide PRN code in C-band and 490 MHz in upper X-band using a software-defined-radio (SDR) receiver can give ionospheric free one-way-ranging measurement that will be superior to today's GNSS code measurements in terms of precision by a factor 15–25. Simulations have shown that one-way-ranging measurements on the level of 1 mm could be achieved. Provided the satellite local oscillator is suitably stable and the ground station signal chain could be calibrated to a sufficient level, such measurements could be used for differential time and frequency comparison on a global scale. Utilization of the carrier phase offers yet another potential improvement especially for frequency comparison. Combination of the Genesis one-way-ranging measurements with VLBI and/or GNSS promises to improving station clock differences estimation with either technique. We will present the potential utilization of the Genesis mission for time and frequency transfer between remote VGOS stations. These are usually equipped with active H-masers and some of those stations also realize a UTC(k), thus a time metrological connection to geodesy is given. The potentially high performance of the ionospheric free code and carrier phase ranging makes it interesting to be used for frequency comparison of optical frequency standards, that we can expect to be part of or to be connected to VLBI installations in the future.

Advancing Rubidium Pulsed Optical Pumping (Rb POP) atomic clock for Galileo experimental flight

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G3: Vapor-cell deployable clocks, April 23, 2026, 13:30 - 15:00

In this paper, we present our latest results on the promising Rubidium Pulsed Optically Pumped, originally developed at the Italian National Metrology Institute (INRiM) and now being transferred and industrialized by Leonardo, under the guidance of the European Space Agency (ESA), funded by the European Union programme Horizon Europe and coordinated by European Commission DG DEFIS.

The Rb POP is among the new clock technologies selected for completing on ground qualification and performing in orbit validation on board second-generation Galileo satellites as experimental clock.

Rb POP is a warm vapour cell frequency standard where an excellent control of systematic effect is obtained by using a Ramsey interrogation scheme of the 87Rb clock transition, allowing to achieve a short-term stability comparable to a Hydrogen maser, extending into the 10-16 range, and a long-term drift at the level of 10-14/day.

Space designed Physics Package (PP) has been developed and extensively tested in the first stage of the program and currently the Optics Package (OP) and the Electronics Package (EP) are being integrated and tested in a full clock configuration for functional and performance characterization in ambient conditions.

The Rb POP program is currently under critical design review (CDR) aimed at completing the detailed design phase and release the construction of an experimental flight model and an engineering qualification model.

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A multi-ion optical clock with 5.3×10^-19 systematic uncertainty

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G6: Ion optical clocks, April 21, 2026, 10:45 - 12:15

We present a new optical clock based on the $^2S_{1/2}$ - $^2D_{5/2}$ transition in 88Sr+ with a fractional systematic uncertainty of 5.3×10^-19. Despite the transition's strong sensitivity to external fields, we control shift effects not only for a single ion but also for linear ion chains and routinely operate the clock with up to 10 ions.

An optical clock comparison between the new system and an established single-ion clock based on the $^2S_{1/2}$ - $^2F_{7/2}$ transition in 171Yb+ yields consistent results between the Sr+ clock operating with either a single or up to 10 ions. Operation with multiple ions significantly reduces the measurement instability. For the frequency ratio, we achieve a statistical uncertainty of 0.9×10^-18 and a systematic uncertainty of 2.8×10^-18, limited by that of the Yb+ clock .

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Pinched Hysteresis within 1:1 Coupled MEMS Resonator

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G4: Micro and nano resonant sensors, April 22, 2026, 15:30 - 17:00

We show for the first time that a 1:1 coupled MEMS resonator device can be used to observe a cross-domain pinched hysteresis in the amplitude response, which is a hallmark characteristic of a memristor. This shows great promise for further research into coupled resonator memristor-like devices, which are ideally placed to be used as a key component for in-sensor computing, neuromorphic computing and AI hardware. This is achieved by coupling the intrinsic resonant modes of the device, without the need for nonlinear operating schemes such as parametric modulation, which has been shown previously.

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A commercial single-ion optical frequency standard with a systematic uncertainty below 2E-17

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G6: Commercial optical clocks, April 23, 2026, 08:45 - 10:15

We present the first commercially available single ion optical frequency standard (OFS) based on $^{171}Yb^+$ and completely integrated in two 19" racks. The OFS has been transported to PTB in June 2025 for a full metrological evaluation within the EU project Qu-Test. In comparison with the more stable optical frequency standard PTB-Yb1E3, a frequency instability of 5E-15/√τ with a total systematic uncertainty below 2E-17 of the OFS was demonstrated and even for averaging times beyond 10^5 s, the system shows white frequency noise behavior.

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Progress Towards the Development of a Compact and High-Performance Cs CPT Clock

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G3: Vapor-cell deployable clocks, April 23, 2026, 13:30 - 15:00

We report here a transportable CPT clock relying on a compact electro-optical bench and selected COTS low-noise electronics. The bench is opto-mechanically integrated within a 45 × 45 × 10 cm^3 volume and assembled entirely from COTS free-space, fibered optical, and electro-optical components. The laser and magnetic field current sources, as well as the PID for CPT cell temperature regulation and for laser intensity and frequency stabilization loops, are all COTS elements selected for their low-noise performance over both short and long timescales. The RF synthesis and the digital electronics, developed and validated by INRIM were used to optimize the clock performance during the joint experimental campaign at TRT. The preliminary characterizations of this clock, operated in Ramsey-CPT mode, led us to obtain a fractional frequency stability around 5×10-13 at 1 s.

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Transportable optical clock for remote comparisons and contributions to timescales

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G6: Commercial optical clocks, April 23, 2026, 08:45 - 10:15

We report on recent improvements to our transportable optical clock Opticlock , contributions to recently conducted international campaigns, and how the system is employed to realize local timescales and contribute to the international atomic timescale (TAI).

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Continuous-wave laser source at the 148 nm nuclear transition of Th-229

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G6: Advanced optical clocks, April 21, 2026, 13:30 - 15:00

We will present an all-solid-state approach for the CW VUV laser system of a Th-229 nuclear clock based on frequency doubling of laser radiation at 297 nm using second-harmonic generation in strontium tetraborate (SBO).

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ACES Microwave Link Architecture

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G5: Microwave TFT in space, April 22, 2026, 13:30 - 15:00

The ACES Microwave Link (MWL) consists of a space segment on-board the ISS (International Space Station) and several ground terminals deployed in Europe, US, and Japan.
We describe the link design, consisting of one bi-directional link in Ku-band and one down-link in S-band. All are modulated using pseudo-noise codes, containing a 1 pps marker for time transfer and ambiguity resolution.The modulation is designed to resolve the cycle count on the carriers.
The MWL units implement a continuous time scale driven by the connected clocks, space and ground. The received time scale is time tagged against the local time scale. The event timer for the ELT (European Laser Timing Experiment) inside on-board MWL electronics is equally connected to this time scale. On-board data of ELT are included in the MWL science data.
The available measurands are described, which include ranges and pseudo ranges, as well as derived quantities to determine the dispersive properties of the propagation through ionosphere.
For system verification prior to launch, ground terminal electronic units have been used in back-to back condition to characterise the static and dynamic link properties under realistic orbit conditions, incl relative velocity and variable signal amplitudes.
This set-up was used as test-bed to verify the measurement process, to optimize data handling and improve our understanding of the limiting factors and error sources for the design of such space-to-ground links.
An outlook is provided, how this could lead to more advanced link designs.
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Optical frequency standards on the move: land, sea, and space

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G6: Deployable optical clocks, April 22, 2026, 15:30 - 17:00

Summary: Portable optical atomic clocks offer time and frequency reference signals with a short-term performance better than current state-of-the-art commercial systems. Here we present the development of several optical frequency standards based on spectroscopy of neutral ytterbium and rubidium. We have tested the reliability and resilience of these clocks through multiple field trials, including in preparation for an imminent space launch.

The full range of potential applications for atomic clocks is only realizable if they can be operated outside of stringent lab conditions. Thus, while typical figures of merit for high performance clocks focus on phase noise, frequency instability and accuracy, one must take account of additional requirements for deployable devices including size, weight, and power (SWaP), complexity, component maturity, and robustness in harsh, dynamic, and unsupervised environments.

I will describe three separate projects:

[a] a ship-borne trial involving two vapour-cell frequency standards - one based on dual-colour excitation of a Doppler-free, two-photon transition of rubidium showing ~1 x 10-13/$\sqrt{\tau}$ frequency stability, and a second based on the 1S0 ↔ 3P1 transition in ytterbium. Both standards incorporate frequency combs that convert the optical outputs into the microwave domain. We will also present data on more recent variants of the Yb standard.

[b] a second ship-borne trial of a frequency standard based on a laser-cooled atomic beam of neutral ytterbium atoms. The physics package contains a Yb oven, transverse 2D cooling stage using the 399 nm 1S0 ↔ 1P1 transition, a Ramsey-Bordé interrogation of the 1S0 ↔ 3P0 clock transition, and a velocity sensitive detection stage on the 1S0 ↔ 3P1 line. The exclusive use of fibre lasers, combined with in-vacuum interrogation optics, minimises alignment, vibration, and temperature sensitivity. The 578 nm clock laser was pre-stabilised using an internal frequency comb to transfer the coherence from the Yb vapour cell clock described in project [a] above. The entire package was 150 kg, 0.5 m3 in size, and consumed 770 W. The device demonstrated a frequency stability of 2 × 10-14/$\sqrt{\tau}$ up to 200 s.

[c] the development of space-qualified version of the Rb standard described in [a]. This has seen a SWaP reduction to 18 kg, 20 L, and <70 W, with successful qualification against the vibration, thermal vacuum, and radiation requirements for satellite launch. A clock sub-system, based on this standard's frequency comb, is due for a launch in Q1, 2026 and I will describe the journey that has got us to this point.

[1] Hilton, A. P et al, "Demonstration of a Mobile Optical Clock Ensemble at Sea," Nat. Com. 16, 10.1038/s41467-025-61140-2.
[2] Offer, R. F et al," A portable laser-cooled ytterbium beam clock … ", provisional acceptance, Optica (2026).

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Frequency characterization of chip-scale frequency combs

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[1]RISE Research Institutes Of Sweden

Poster session 1, April 21, 2026, 15:30 - 17:00

Optical frequency combs underpin modern optical frequency metrology, and recent advances have enabled compact chip-scale implementations known as microcombs. RISE, in collaboration with Chalmers University of Technology, is developing capabilities to characterize these devices for metrological applications. Our work focuses on understanding soliton microcomb generation and accurately determining key parameters such as repetition rate, and optical linewidth. We present measurement techniques based on electro-optic downconversion for repetition-rate and phase-noise analysis, and a self-heterodyne interferometric method for linewidth determination. These developments provide a framework for assessing the stability and spectral purity of chip-scale frequency combs.

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Development of a molecular iodine optical frequency reference at RISE

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Poster session 2, April 23, 2026, 15:30 - 17:00

The use of hot vapor cells as optical frequency references is attracting growing interest due to their low size, weight, and power (SWaP) and their frequency stability comparable to leading microwave standards used in timekeeping. In anticipation of the redefinition of the second based on optical transitions, RISE is strengthening its national capability in optical frequency metrology. This contribution presents ongoing work on developing a high-performance iodine-stabilized laser system serving as the first optical frequency reference at RISE. Molecular iodine provides narrow, well-characterized absorption lines near 532 nm, enabling a long-term performance competitive with hydrogen masers. We will present the overall strategy of the system comprising a compact, transportable spectrometer using modulation transfer spectroscopy. Designed as both a potential optical flywheel oscillator for time scale applications and a complementary reference to the 633 nm realization of the metre, this work marks a key step toward national optical frequency traceability.

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Long-Term Time Transfer Performance Evaluation of a Low-Cost GNSS Receiver Module

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Poster session 1, April 21, 2026, 15:30 - 17:00

Global Navigation Satellite System Time Transfer (GNSSTT) is the most economical and widely adopted approach for achieving long-baseline, nanosecond-level time transfer. Over 80% of the UTC time transfer data submitted to the BIPM rely on GNSSTT links. For National Metrology Institutes (NMIs), redundancy and long-term stability monitoring are essential to ensure reliable results. Using multiple GNSS receivers and comparing their outputs can main-tain link integrity and reduce the risk of single-receiver failure. In such cases, low-cost GNSS receivers provide an economical secondary link solution. They are also attractive for industrial applications requiring nanosecond-level synchronization, such as power grids and telecommu-nications.

Over the past decade, several studies have investigated the use of low-cost GNSS receivers for time comparison, confirming that dual-frequency low-cost receivers can achieve nanosecond-level accuracy .

This study focuses on evaluating the long-term performance of a low-cost GNSS receiver. A modular receiver (Septentrio AsteRx-m3 Pro+, designated TL3A) was in-stalled and continuously monitored over a 90-day period, with its common-view (CV) data compared to that of a reference receiver (Septentrio PolaRx5TR, designated TLT5). For benchmarking, a reference pair (TLT5–TL1A), consisting of two PolaRx5TR receivers, was op-erated concurrently.

During the monitoring period, the TL3A receiver was periodically powered off and restarted to assess the stability of its internal hardware delays. The results indicated that the hardware de-lays for all observation codes remained unchanged before and after reboot.

In terms of time transfer performance, the RMS Time Interval Error (TIE) for the TLT5–TL3A CV results was approximately 220 ps, compared to 170 ps for the reference pair (TLT5–TL1A). However, a subtle but consistent drift was observed in the L1C, L1P, and E1 observations of TL3A, resulting in a slope of approximately 5 ps/day in the TLT5–TL3A P3 CV results over the 90-day period (Figure 1). Continuous monitoring will be conducted to further validate the long-term stability of the TL3A receiver.

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GIASONE-2: A Scalable and Authenticated Infrastructure for Advanced GNSS Signal Integrity Monitoring

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[1]Intecs Spa

Poster session 1, April 21, 2026, 15:30 - 17:00

The reliability of GNSS services has become an essential prerequisite for safety-critical sectors. The rising prevalence of threats like jamming and spoofing necessitates the adoption of robust, advanced surveillance infrastructures. The GIASONE-2 project (Enhancement GNSS Integrity and Authentication Services User-Oriented Network), co-financed by ESA, addresses this need by introducing a modular, scalable, and user-oriented system for real-time GNSS signal monitoring, analysis, and authentication.
The architecture is designed as a network of different units, each with peculiar capabilities, built upon resilience and reconfigurability. The system consists of a variable number of ARGO Stations (high-performance fixed ARGO-2S and mobile/compact ARGO-ST) distributed at the regional/interregional level and a CDPU (Central Data Processing Unit), for data aggregation and processing. The core technical element is the use of SDR (Software Defined Radio) technology in the ARGO stations. This ensures unparalleled reconfigurability and operational lon-gevity, allowing for the integration of new functionalities and the extension of monitoring to new bands and constellations (e.g., GPS L2/L5, Galileo E5, GLONASS G1/G2, BeiDou B1/B2) with minimal hardware impact.
GIASONE-2 introduces significant enhancements to interference detection and mitigation capabilities:
1. Advanced Interferer Detection and Localization: The system implements new algorithms for more accurate Radio Frequency Interference (RFI) classification. The most significant innovation is the integration of Direction Finding (DF) Antennas into the ARGO stations. By connecting multiple DF stations in a network, the system enables high-precision triangulation techniques to locate the physical source of the disturbance (jamming/spoofing), a crucial capability for competent authorities.
2. Resilient Signal Authentication: In addition to pre-existing cross-correlation methods, GIASONE-2 integrates further authentication strategies, including full processing capability for the Galileo OSNMA (Open Service Navigation Message Authentication), creating a more robust multiple authentication system that is highly resilient to compromise.
The system will undergo testing and validation in a significant operational environment (Grottaglie airport, in partnership with ENAV S.p.A.), focusing initially on the airport domain to meet ICAO directives and EU Regulation 2020/469.
In conclusion, GIASONE-2 is not merely an upgrade, but a technological leap that combines hardware innovation (SDR, DF) and algorithmic advancements (multiple authentication, RFI localization) to solidify a premium GNSS platform, which is essential for the security and re-silience of critical European and global infrastructures.

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P-B1 - Piezoelectric MEMS-enabled acoustic phonon pulses for high-speed modulation in terahertz quantum cascade lasers: Direct comparison of ZnO-based SAWs and BAWs

Dr. Alkausil Tamboli[1], Dr. Mohammed Salih[1], Professor John Cunningham[1], Professor GILES-DAVIES Alexander[1], Mr. Mohammad Zaid
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Poster session 1, Atrium and B9, April 21, 2026, 15:30 - 17:00

The terahertz quantum-cascade laser (THz QCL) is a compact, electrically pumped source lever-aging intersubband transitions. Their picosecond carrier-lifetime make them suitable for ultra-fast modulation, typically achieved via fast control of applied bias modulating the current flow. However, modulation bandwidth is limited (to<20 GHz) by parasitic effects. Alternative methods, such as graphene-based modulators or monolithic integration, offer improved performance but remain constrained by capacitive limitations . Recently, ultrafast modulation using optically generated picosecond acoustic pulses was demonstrated, bypassing electronic limits, though with limited modulation depth of ~6% due to low strain amplitudes ~10^{-6}. Piezoelectric transducers, capable of generating coherent phonons at up to 97 GHz with higher strain, offer a promising route to enhance modulation speed and depth . In this study, finite element analysis (FEA) was employed to perform a direct comparison between surface acoustic wave (SAW) and bulk acoustic wave (BAW) actuation for generating coherent phonon pulses aimed at achieving high-speed modulation THz QCLs. For a fair comparison, the ZnO piezoelectric layer thickness in both configurations was fixed at 1.5 µm. In each case, the piezoelectric transducer was positioned atop the QCL active region. The SAW-based device, with a 10 µm pitch, exhibited a resonant frequency of 215 MHz, while the BAW configuration demonstrated a resonant frequency of 1.415 GHz. The strain amplitude within the QCL active region under SAW excitation ranged from 2×10^{-6} to -12×10^{-6} across the device depth. In contrast, the BAW-driven actuation produced significantly higher strain amplitudes, in the range of $0.5–1\times10^{-2}$. These findings reveal that BAW-induced strain amplitudes are approximately 10^4 times greater than those achieved through SAW excitation and those reported for optically generated strain pulses. The simulation results therefore suggest that piezoelectric BAW-based actuators present a highly promising route for realizing strain-induced, high-speed modulation in THz QCLs.

P-B17 - Influence of temperature on the Q-factor of dual-mode solidly mounted resonators for sensing applications

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Poster session 2, Atrium and B9, April 23, 2026, 15:30 - 17:00

Dual-mode solidly mounted resonators (SMRs) are capable of simultaneously measuring both mass and temperature and have been effectively demonstrated as highly sensitive biosensing de-vices. Due to their intrinsic temperature sensitivity, these piezoelectric resonators are typically ovenized to maintain precise temperature control. For biosensing applications, achieving a high quality factor (Q-factor) is essential, as it minimizes system noise and signal interference, thereby ensuring reliable detection and reducing the likelihood of false positives or negatives. However, elevated temperatures resulting from ovenization generally lead to a deterioration of the Q-factor. The exact influence of temperature on the mechanical and dielectric losses within piezoelectric resonators is not yet fully understood, leaving the precise temperature dependence of Q uncertain. Nonetheless, Kim et al. reported a clear temperature dependence of Q in MEMS resonators, which can be extended to piezoelectric MEMS systems, suggesting an inverse correlation be-tween Q-factor and temperature [1]. In this study, the temperature dependence of both resonant modes in a dual-mode SMR is investigated experimentally, as maintaining high Q values at elevated temperatures is critical for consistent and accurate biosensing. The measured Q-factors for both modes across a temperature range of 25 °C to 100 °C are presented in Figure 1. This temperature range was selected as most proteins begin to denature beyond 70 °C. A decline in both the resonant (Qr) and anti-resonant (Qa) Q-factors with increasing temperature was observed, at-tributed primarily to intrinsic loss mechanisms in piezoelectric materials. As temperature rises, enhanced thermoelastic damping and phonon–phonon scattering lead to greater energy dissipation, thus lowering the Q-factor. Specifically, for Mode I, Qr decreased from 761 at room temperature to 602 at 100 °C, while Qa dropped from 425 to 144. Similarly, in Mode II, Qr declined from 676 to 569 and Qa from 592 to 239 over the same temperature range. However, the Q-factors ob-served at 100 °C for both modes are still above 140, which is sufficiently high to achieve reliable sensing.
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Design of a MEMS-based photo-acoustic pressure sensor – Resonant approach

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Poster session 2, April 23, 2026, 15:30 - 17:00

In healthcare applications such as analysis of exhaled air for medical diagnosis, there is a need for low-SWaP-C, high-resolution, selective gas sensors capable of performing in real time. Recent years have seen the promising development of several approaches based on the joint use of photo-acoustic emission and (silicon) MEMS or quartz resonators . The ANR-funded ATLAS project investigates new concepts of photo-acoustic MEMS transducers in order to bridge the gap, in terms of precision, with existing quartz approaches. One of these concepts is the development of a narrowband acoustic pressure transducer based on a MEMS membrane separating a vacuum cavity from the gas mixture at ambient pressure . The laser responsible for photo-acoustic emission is modulated at the membrane resonance frequency to generate the largest out-of-plane displacement for a given amount of acoustic pressure. We have shown that the thermal noise floor of this approach is in the range of 100s of nPa/Hz1/2, but that amplifier noise may degrade this figure if capacitive transduction is used. In this paper, we study the use of in-plane resonant gauges, whose stiffness is parametrically modulated by membrane motion, as an alternative to the capacitive approach (Fig. 1 & 2). In order to achieve optimal performance - coinciding with parametric resonance - the in-plane resonator frequency must be tuned to that of the membrane. Supported by an analytical model and finite element simulations, we argue that this tuning condition can realistically be achieved in spite of fabrication uncertainties and that parametric resonance can be harnessed to resolve the sub-pm/Hz1/2 thermal motion of the membrane.

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Digital design of high-precision magnetic field for hydrogen maser

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Poster session 2, April 23, 2026, 15:30 - 17:00

Hydrogen maser is the time and frequency reference source of metrology, punctuality and scientific research in China, and it is the core equipment of national important projects such as deep space exploration, navigation and positioning. In this paper, a scheme to realize the digitization of magnetic field of hydrogen atomic clock is presented. We first design a simple programmable precise current source. And then we use a microprocessor-based intelligent control algorithm to automatically find the maximum power point corresponding to the output voltage of the single-chip microcomputer. Finally, the constant output voltage. In the actual test process, we designed the constant current source circuit output current step quantity can achieve 5uA high precision, spectrum analyzer sampling efficiency and the control system work accuracy is very high.

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Temperature control optimization for Cryogenic Sapphire Oscillator

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Poster competition, April 21, 2026, 15:30 - 17:00

FEMTO-ST has developed ultra-stable Cryogenic Sapphire Oscillators (CSOs) achieving fractional frequency instabilities below 3×10^{-15}. However, a degradation in short-term stability is consistently observed around a 10-second integration time, suggesting a temperature-related limitation. To investigate this, the temperature regulation system based on a commercial PID controller was thoroughly analyzed through combined thermal simulations and cryogenic measurements. The developed thermal model shows strong agreement with experimental data and provides a foundation for optimizing temperature control, with the goal of further improving the frequency stability of CSOs.

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Smart Sensor Fusion for Robust Initialisation and Accurate Trajectory Estimation

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Poster session 1, April 21, 2026, 15:30 - 17:00

Reliable navigation has become a safety-critical requirement for aerospace, automotive, and autonomous platforms. Global Navigation Satellite Systems (GNSS) provide globally referenced position and velocity, but their performance degrades under signal blockage, interference, or jamming. In contrast, Inertial Measurement Units (IMUs) deliver high-rate motion information independent of external infrastructure, but suffer from bias drift and unbounded integration errors. This work presents a robust, fully reproducible framework for post-processing GNSS+IMU datasets, focusing on the initial alignment problem and the subsequent fusion pipeline.
The first contribution of this work is a systematic comparison of three classical closed-form solvers for Wahba's Problem—TRIAD, Davenport's Q-method, and Singular Value Decomposition (SVD). Using accelerometer-derived gravity and gyro-compassed Earth rotation vectors, each solver computes the initial orientation between body and navigation frames. Experimental evaluation demonstrates sub-degree alignment accuracy, with SVD achieving a balanced distribution of error between tilt and heading, while TRIAD and Davenport prioritize gravity alignment.
The second contribution is the design and implementation of a 15-state error-state Extended Kalman Filter (EKF) for loosely coupled GNSS/INS integration. The EKF estimates navigation errors and IMU sensor biases, fusing high-rate inertial data (400 Hz) with low-rate GNSS updates (1 Hz) in Earth-Centered Earth-Fixed (ECEF) and North-East-Down (NED) frames. The filter achieves decimeter-level 3D Root Mean Square Error (RMSE) and final position accuracy on the order of centimeters over a 52-minute high-dynamics trajectory. Additional innovations include a robust time-synchronization algorithm to resolve integer-second ambiguity between IMU and GNSS timestamps, and an automatic lift-off detection algorithm using accelerometer thresholds. These ensure reliable transition from static alignment to dynamic fusion without manual intervention. The pipeline is implemented in Python (3.10+) and MATLAB, validated with automated unit tests, and released as an open-source repository for reproducibility.
The presented results confirm that, under continuous GNSS aiding, the specific choice of initial alignment algorithm has negligible impact on downstream accuracy, provided sub-degree initialization is achieved. Instead, the critical factors for sustained performance are reliable time synchronization, bias estimation, and robust EKF tuning. The developed framework serves as both a reference design for navigation researchers and a practical testbed for future extensions such as tightly coupled carrier-phase updates, magnetometer augmentation, and multi-GNSS integration.

Description of new and innovative aspects of the presentation:
• Direct benchmarking of classical Wahba solvers (TRIAD, Davenport, SVD) under real IMU/GNSS conditions. • A reproducible, open-source GNSS+IMU pipeline with modular design and automated validation. • Integration of timing ambiguity resolution and lift-off detection for fully automated execution.
• Demonstrated sub-degree initial alignment and centimeter-level trajectory accuracy over extended flight data.

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Towards the realisation of Transportable Optical Lattice Clock with Strontium Atoms

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Poster session 2, April 23, 2026, 15:30 - 17:00

This report presents the recent advancement towards the transportable optical lattice clock (OLC) with strontium 88 atoms at the University of Birmingham, UK. The aim is to transport a fully operational OLC to the National Physical Laboratory (NPL) in London for the clock comparison campaign. The compact physics package of OLC is integrated with UHV, electromagnets, suitable light beam deliveries and an imaging and detection system required for clock operation in <150 L. Along with the physics package, the rest of the system, including the ARTIQ-based computer control module, lasers, laser controllers, frequency comb and ULE cavity, will be transported together via two 19-inch racks. Recently, clock spectroscopy is successfully achieved.

Keywords—Optical lattice clock; Transportable; Strontium; Compact;

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White Rabbit-based distributed clock ensemble for increased timing resilience

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Poster session 1, April 21, 2026, 15:30 - 17:00

As critical infrastructures increasingly depend on precise and resilient PNT capabilities, the vulnerabilities of GNSS have become exposed. Complementary PNT (C-PNT) initiatives have therefore emerged to reinforce service availability and operational robustness. The ITU-T recommendation coherent network PRTC (cnPTRC) promotes the use of distributed clock ensembles to improve timing performance and fault tolerance, but current implementations typically depend on a small number of expensive ePRTC nodes distributed across a country and this limits scalability and cost effectiveness. A cost-effective distributed clock ensemble is presented, implemented as a White Rabbit mesh network of Rubidium standards that delivers high-accuracy synchronization with reduced infrastructure cost. The White Rabbit fabric provides sub-nanosecond timing distribution that enhances the effective stability of deployed Rubidium references and enables seamless, dynamic joining and leaving of nodes while preserving a unified ensemble timescale. Tests executed at ESA/ESTEC Time and Frequency Laboratory with Caesium clocks and the White Rabbit mesh demonstrate timing stability and resilience in line with model predictions and deployment requirements. In addition, the ensemble fusion algorithm incorporates explicit mitigations for phase jumps and frequency steps, including detection and adaptive weighting, which together maintain continuity and coherence of the timescale under abrupt disturbances and component degradation. Reported metrics include Allan deviation, time error over relevant averaging intervals and availability under induced perturbations; discussion covers system scaling, fault tolerance and integration pathways for C-PNT architectures in critical infrastructure environments. This work was supported by ESA's Navigation Innovation Support Programme (NAVISP) Element 2.

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Research on shared laser cesium atomic clocks

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Poster session 2, April 23, 2026, 15:30 - 17:00

The introduction of laser detection to replace magnetic detection in cesium atomic clocks can effectively address the lifespan limitations caused by electron multipliers. However, lasers increase the system's volume, weight, and cost. The overall volume, weight, and cost of the system can be reduced by having multiple cesium atomic clocks share the same laser. This paper discusses whether sharing a laser between two cesium atomic clocks would reduce the independence of their output clock signals. It was found that as long as the microwave modulation signals of the two cesium atomic clocks are not in phase, independence is not compromised.

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Graphene Parametric Oscillator

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Poster session 1, April 21, 2026, 15:30 - 17:00

The stability of frequency is crucial for high-precision sensing applications with nanoresonators. While conventional methods favor operation in the linear regime of the resonators to minimize the frequency fluctuations, recent studies suggest that nonlinear dynamics can improve frequency stability. This work investigates the frequency stability of graphene nanoresonators at parametric resonance in a closed-loop using a phase-locked loop (PLL), aiming to understand how parametric phenomena affect frequency stability for future resonant sensing and time-keeping applications. The frequency stability is evaluated using Allan deviation, which quantifies fluctuations over different timescales.
In this work, the experiments are conducted using 12 µm diameter bilayer graphene nanodrums, where the nanodrum is actuated optothermally with a blue laser and its motion is read out via a red He-Ne laser. The experiments begin with frequency sweeps at varying drive amplitudes, where the drive frequency is twice the reading frequency for the parametric excitation. Next, a PLL is implemented to perform closed-loop operation. The PLL points are set close to the direct resonance frequency, which is also the bifurcation region for the parametric response. Upon configuring the PLL for each operation point, the frequency is recorded for 3 minutes, and these measurements are used to calculate the Allan deviation. It is shown that the parametric response is more stable than the direct response in the vicinity of the direct resonance.

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Integrating Artificial Intelligence into Atomic Clock Systems

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Poster session 1, April 21, 2026, 15:30 - 17:00

Atomic clocks are essential for precision timestamping and synchronisation in digital infrastructure and mission-critical systems. While highly accurate, their medium- to long-term stability is compromised by environmental fluctuations, component aging, and physical effects such as light shifts, collisional broadening, and Zeeman shifts that perturb atomic transitions.
Traditional clock control strategies rely on predefined models to correct known errors reactively, which limits adaptability to evolving conditions. Artificial Intelligence (AI) offers a significant improvement by enabling predictive capabilities and feedforward corrections. Specifically, deep learning models like Long Short-Term Memory (LSTM) networks can learn complex, nonlinear patterns from historical data, even when underlying physical causes are not fully understood.
Our LSTM model using historical satellite clock data show that it can accurately forecast future frequency deviations and detect anomalies. This approach enhances clock stability by improving holdover duration and reducing Allan deviation over medium to long timescales ($\tau > 100$ s). However, historical-data-informed models alone cannot anticipate sudden, previously unseen events, such as power surges, which are detectable through real-time telemetry.
To address this limitation, a telemetry-informed AI model is proposed. It learns correlations between sensor inputs and clock performance in controlled environments, enabling proactive compensation and real-time diagnostics. Combining both approaches, historical-data-informed and telemetry-informed into a hybrid AI architecture provides a robust solution. In this architecture, historical models would manage long-term trends, while telemetry models would handle real-time anomalies.
This hybrid AI framework represents a transformative step toward proactive, intelligent atomic clock management, improving stability and reliability in critical applications.

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An Improved Algorithm for Sub-LOF Anomaly Detection Based on Bayesian Optimization

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Poster session 1, April 21, 2026, 15:30 - 17:00

Atomic clocks, serving as the core instrumentation for precision timekeeping, have their stability and reliability directly impacting the development of numerous fields, including Global Navigation Satellite Systems (GNSS) and fundamental time-frequency metrology. However, the occurrence of anomalous signals during atomic clock operation is inevitable, which can significantly degrade their time-keeping performance. Conventional anomaly detection methods heavily rely on manually set thresholds or predefined clock noise models, struggling to adapt to the non-stationary characteristics inherent in atomic clock data and exhibiting poor generalization capability.

Unsupervised machine learning offers a novel pathway for atomic clock anomaly detection. Nevertheless, existing studies present certain limitations: firstly, the critical hyperparameters of algorithms often depend on empirical or default settings, lacking systematic optimization, which constrains the full exploitation of detection performance. Secondly, the synthetic data used for algorithm validation are frequently overly idealized, failing to accurately simulate the complex power-law noise characteristics intrinsic to atomic clock signals, thereby compromising the reliability of evaluation outcomes.

To address these challenges, this paper proposes an enhanced subsequence local outlier factor (Sub-LOF) outlier detection algorithm optimized with Bayesian Optimization. Initially, for the well-performing Sub-LOF algorithm, we move beyond fixed default parameters by introducing Bayesian Optimization to conduct a systematic hyperparameter search. This aims to identify the optimal parameter configuration for different clock types and sampling rates, thereby maximizing anomaly detection performance. Concurrently, a power-law spectral noise model is employed to generate highly realistic clock error data, precisely simulating various typical noise types to provide a more reliable benchmark for both algorithm optimization and evaluation. Finally, validation is performed using a combination of synthetic data and real atomic clock data from cesium clocks and hydrogen masers.

Experimental results demonstrate that, compared to traditionally synthesized data, simulation data based on power-law spectral noise more accurately reflects algorithm performance in practical applications. Furthermore, the Sub-LOF algorithm tuned via Bayesian Optimization shows significant improvements over the baseline method using default parameters, across the evaluation metrics of Precision, Recall, and F1-Score. This study not only enhances the accuracy and robustness of atomic clock anomaly detection but also establishes a more rigorous paradigm for data generation and parameter optimization in the validation of machine learning algorithms within the field of precision time and frequency metrology.

Metrological study of a self-linewidth-narrowing photonic oscillator based on stimulated Brillouin scattering

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The REFIMEVE research infrastructure delivers a frequency reference of metrological quality to more than 30 French research laboratories. It provides an exact and stabilized optical refer-ence in the telecom wavelength, originating from the French national metrological institute, LTE-OP of the Paris Observatory, and distributed by LTE and the Laser Physics Laboratory (LPL), using the optical fibers of the RENATER network , . To limit the degradation of the sig-nal's stability caused by propagation through the fibers, the REFIMEVE infrastructure includes several regeneration stages that compensate for the accumulated frequency noise. However, the very long fiber lengths and the number of regeneration stages degrade the short-term frequency noise of the signal (particularly between 10 Hz and 1 kHz), reaching up to a few kHz linewidths for averaging time of 100 ms for links of length >100-1000 km (Paris-Marseille) .
For some remote users, even though the signal's accuracy is preserved, its linewidth remains too large for their applications. It is therefore of interest to develop a solution that ensures improved frequency noise spectral density performance while maintaining a compact and user-friendly system. One solution is to lock a laser with an intrinsically low frequency noise spectral density (from 10 Hz to 10 MHz, and particularly between 10 Hz and 1 kHz) to the REFIMEVE signal to compensate for its long-term fluctuation.
This work aims to study the behavior of a new type of laser: a spectrally self-narrowed oscilla-tor based on the stimulated Brillouin effect, operating without electronic feedback. Initially de-veloped at the FOTON Institute , it has been patented and transferred to the Silentsys company.
This source exhibits a noise floor at high frequency of 10-4 Hz^2/Hz at 1MHz when measured with Silentsys frequency discriminator. The short term and long-term behavior is studied at LPL by beating with the "Hz level stability" of the REFIMEVE signal at LPL. Preliminary results show an agreement of the frequency noise measurement (cf. figure), and long-term frequency drift below 5MHz/h 2 days after transportation when the laser is not yet fully thermalized

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Miniaturized setups for magneto-optical trapping of ytterbium and strontium

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Poster session 2, April 23, 2026, 15:30 - 17:00

Optical lattice clocks based on ytterbium (Yb) and strontium (Sr) are emerging as key technologies in precision timekeeping and metrology. Recent advancements in miniaturization and transportability are making them increasingly accessible for applications outside traditional laboratory settings. However, the degree of miniaturization is limited by the atomic source that is used to provide laser-cooled atoms for the clock spectroscopy. Conventional atomic sources for optical lattice clocks consist of a high-power oven and a magneto-optical trap (MOT) that requires six incident laser beams for three-dimensional trapping and cooling.
Here, we present technologies that allow a significant miniaturization of the required experimental setups to realize a MOT for Yb and Sr. These are a chip-based microstructured atomic oven and in-vacuum optical elements that require only a single incident laser beam to generate all of the required beams for three-dimensional trapping and cooling. The oven was manufactured with LIDE® (laser induced deep etching). It was paired with an aluminum pyramid reflector to load Yb atoms into a MOT. The oven was placed directly at the outside of the reflector, forming a compact setup that is used for atom evaporation and direct trapping and cooling. In this configuration, MOT loading rates above 10^8 atoms/s were measured for oven heating powers below 250 mW. Furthermore, the microstructured oven was paired with a grating MOT chip inside a highly compact vacuum chamber. The chamber was additively manufactured from titanium and the assembled setup spans a volume of less than 750 ml. In this setup, up to 10^5 Sr atoms were trapped in the MOT.

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Piezo-electrically tunable metrological Fabry-Perot cavity for a continuous superradiant laser

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Poster competition, April 21, 2026, 15:30 - 17:00

Fabry-Perot (FP) cavities are a cornerstone technology in modern optics. They provide essential tools for laser stabilization, frequency transfer and for atom trapping. State-of-the-art ultra-stable cavities can reach fractional frequency stabilities of 2.5 × 10^(-17) at one second but are typically fixed in length. While this makes them ideal for precision metrology, their lack of tunability limits applications in cavity quantum electrodynamics (CQED), large-bandwidth laser locking, coherence transfer or large interferometer tuning. In this work, we present the design and characterization of a highly stable tunable FP cavity developed at FEMTO-ST intended for trapping Yb atoms for a continuous superradiant laser (SRL).

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Progress on the Development of High-Accuracy Lab-Based and Transportable Strontium Ion Optical Clocks at the NRC

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Poster session 2, April 23, 2026, 15:30 - 17:00

Two new optical frequency standards based on the S-D transition of the strontium ion have been under development during the past few years in our laboratory. One of the new clocks will be used in a transportable system for comparisons with optical clocks in remote laboratories, and the other will be used as a new lab-based system. We will present the latest advances with the operation and evaluation of the frequency shifts in the new clocks at the conference.

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A Neural Compensator for Fast Recovery from Frequency Jumps in Temperature-Compensated Crystal Oscillators

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Poster session 1, April 21, 2026, 15:30 - 17:00

To address the slow and oscillatory recovery of traditional PI controllers from sudden frequency jumps in crystal oscillators, this work introduces a neural network-based compensator. It shifts the strategy from parameter tracking to pattern recognition. The model is trained to identify the unique signature of a jump from phase error data and immediately outputs a targeted correction voltage. This "predict-and-preempt" approach enables a faster and more stable re-lock, as validated by hardware tests, offering a more robust solution for precision timing in 5G and industrial systems.

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Design and Implementation of a High-Precision PTP Synchronization Board Based on Chip-Scale Atomic Clock

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Poster session 2, April 23, 2026, 15:30 - 17:00

This paper presents a dedicated hardware board designed to solve the challenge of high-precision time synchronization in next-generation systems like 5G and industrial automation, particularly after the loss of a primary reference.

The core innovation is a dual-reference architecture. It combines a highly stable chip-scale atomic clock (10 MHz) with a GNSS-derived 1 PPS signal for absolute alignment. A central MCU manages the system, configuring a clock synthesizer to generate a low-jitter 125 MHz clock from the atomic reference. This clock is processed by an FPGA to synthesize a complete set of synchronized output signals for various PTP applications.

Experimental results confirm the board achieves nanosecond-level short-term synchronization accuracy and exceptional long-term holdover stability, effectively mitigating the performance decay of conventional systems. This provides a robust, high-precision hardware platform for modern time-sensitive applications.

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Stable Fine Tuning of a DFB Laser and Its Application to High-Resolution Optical Spectroscopic Sensing

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Poster session 1, April 21, 2026, 15:30 - 17:00

This work demonstrates a compact and robust scheme for mode-hop-free fine frequency control and stability assessment of a telecom-band DFB laser, and quantitatively links frequency control to application-level gas identification. Dual parameter control of temperature and injection current delivers 5.18 nm continuous tuning with a 10 pm minimum observable step (OSA-limited). Thirty-minute repeated measurements show no resolvable drift, and the temperature to wavelength relation is highly linear, enabling precise placement on rovibrational features. To assess the practical impact of spectral resolution, HITRAN-based near-IR mixtures (NH_3 plus nine interferents) are synthesized and used to train CNN, MLP, and BiLSTM classifiers at 0.01/0.05/0.10 nm. Only 0.01 nm preserves the fine structure needed for reliable identification, with BiLSTM achieving 96.02%, whereas models fail at 0.10 nm. Resolution–performance curves specify the minimum frequency resolution required for dependable classification in crowded bands.

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Analysis of Run-to-Run Variability in Compressional Acoustic Wave Responses from a Single Water Droplet Using

Quartz Crystal Microbalance

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Poster session 2, April 23, 2026, 15:30 - 17:00

Quartz Crystal Microbalance (QCM) has been used not only in investigating the properties of liquid but also the diverse solid-liquid interfacial phenomena. In 2001, L. McKenna et al. reported the observations of compressional acoustic wave generation in a sessile microdroplet of water placed on a quartz crystal resonator. Ever since, there have been a few follow-up studies on this phenomenon. In this paper, we report on the run-to-run variability of compressional acoustic wave behavior in a sessile water droplet of volume 200 µl placed on a quartz crystal. The frequency shift data from multiple runs indicate differences in the wave patterns. In Run 1, the frequency shift stabilizes quickly with small-amplitude slow-varying fluctuations evolving over time, whereas in Runs 2 and 3, large drops in frequencies are observed. Also, in Run 2, the compressional acoustic waves are generated at regular time intervals of ~250 s. These variations suggest that even under nominally identical experimental conditions, subtle differences in droplet placement, contact angle, or surface interactions may result in pronounced differences in the measured acoustic responses. The inconsistencies also imply that the acoustic field within the droplet may evolve differently in each trial, possibly due to the differences in resonance mode excitation and damping within the domain where the waves propagate. These findings highlight the sensitive nature of the QCM–droplet interaction, showing the need for controlled environmental conditions and repeated trials to obtain reliable responses.

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Divergence effect of atomic beam in Ramsey interferometry

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In the optically pumped Caesium beam tube, the divergence of Cs atomic beam is inevitable; however, less attention was paid to its theoretical analysis, and quite a lot explorations involv-ing the problem of divergent atomic beam gave no comprehensive theoretical analysis or refer-ences about it. A theoretical treatment of the effects of divergent Cs atomic beam on Ramsey fringe in terms of its transition probability and linewidth is presented. Different from the ap-proach of using magnetic selection, Cs atomic beam spread straightly through the regions of optical state preparation, Ramsey cavity and optical detection successively in the optically pumped Cs beam tube. Due to the structure of collimator for producing Cs atomic beam, inevi-tably, atoms propagate divergently with angle. Meanwhile, in order to ensure that the Ramsey signal has sufficient amplitude, the size of cut-off waveguides cannot be too small. This inevi-tably, too, leads to the atomic beam spreading with a constant divergence angle, which caused the first-order Doppler effect.
This paper presents a theoretical analysis of the first-order Doppler effect on Ramsey fringe in the optically pumped Cs beam clock. The analysis requires calculation of the probability of clock transition 6S1⁄2(|F = 3, MF = 0⟩) to 6S1⁄2(|F = 4, MF = 0⟩) considering divergence angle and velocity distribution of atoms. The transition probability and linewidth of Ramsey fringe is evaluated in theory by comparing the case of divergence angle is equal to zero with the case of divergence angle is not equal to zero. And the result suggests that the divergence of atomic beam deterio-rates both the intensity and linewidth of Ramsey central fringe.
With a determined length L between two arms of Ramsey cavity, if the maximum divergence angle θmax is sufficiently small, the linewidth broadening 2ε caused by the first-order Doppler effect is linearly related to the speed of atoms. That is, the ratio of 2ε to π / T is a constant which is independent of the speed of atoms. With considering velocity distribution, we have de-rived the relationship between transition probability (linewidth) of Ramsey central fringe when θmax ≠ 0 and transition probability (linewidth) when θmax = 0. The result shows that if θmax ≤ 0.01 rad, the first-order Doppler effect of divergent atomic beam could nearly be neglected.

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Magneto-Optically Pumped Cesium Clock with Monochromatic Laser in Intermediate Magnetic Field

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Conventional optically-pumped cesium beam clocks adopt lasers of different frequencies for pumping and detecting due to the electric-dipole (E1) transition selection rule. For instance, laser stabilized to 62S1/2|F=3⟩ to 62P3/2|F'=3⟩ (3-3' line) is used to populate atoms in 62S1/2|F=4⟩, with 3-2' cyclic line for detection. Consequently, an acousto-optic modulator is inevitably introduced, which complicates the configuration. To simplify the system, we examine atom–light interaction in an arbitrary magnetic field and develop a novel magneto-optically-pumped method for state preparation. With an intermediate magnetic field employed in the pumping zone, energies and states of atoms are manipulated to unlock originally forbidden transitions. Thereby, the 3-2' detection line can be leveraged for optical pumping owing to opening of the 4-2' channel, and a magneto-optically pumped cesium clock using a monochromatic laser is realized.

In an arbitrary magnetic field, eigenenergies and eigenstates related to cesium D2 line can be acquired by diagonalizing the total Hamiltonian H_"tot" =H_"hfs" -μ_"B" (g_I I+g_J J)·B/ℏ. In a nonzero magnetic field, despite energy splitting, states of different |Fm_F⟩ also mix to generate new eigenstates. Such state mixing unlocks the originally E1 forbidden optical transitions (4-2' line, 3-5' line) via E1-allowed components in the excited states. Temporal evolution of the atomic ensemble is characterized by the master equation. Magnetic field distribution generated by permanent magnets is input as parameters for a transient solution.

Fig. 1 displays the agreement between theoretical and experimental spectrum of |F=4⟩ population with magneto-optical σ^--pumping. In a lower magnetic field, the spectral lines may be categorized into four groups, implying atoms transferred between ground states via different hyperfine structure F' of excited states. As |B| grows, peaks overlap due to energy crossings in intermediate-field regime. Fig. 2 exhibits the Allan deviation of a magneto-optically pumped cesium clock using a monochromatic laser with an optimized laser intensity and polarization in a magnetic field about 100 G. A stability of 1.69×10^(-13)/√τ is demonstrated, with an optimization of nearly twice achieved with respect to optically detected magnetic-state-selected scheme without pumping.

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Optomechanical Cooling in a VCSEL-MEMS Laser

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Quantum mechanics typically apply to microscopic particles including molecules, atoms and sub-atomic particles. However, the advancement of laser cooling techniques has established even a macroscopic micromechanical resonator (>10^10 atoms) in its quantum mechanical ground state. The ground-state cooling is typically achieved by coupling mechanical resonators to high-finesse optical cavities with the laser wavelength being tuned to the positive edge of optical resonance. However, the cooling of mechanical resonators via these passive cavities not only require high-finesse but also is effective only for a limited range of wavelengths. Inspired by the idea of laser optomechanics, we demonstrated the use of an active-optical cavity for high-efficient cooling of mechanical resonators. In this work, by solving semiconductor laser equations, we found that the degree of cooling depends on the wavelength-dependent profiles of both optical gain and mirror reflectivity. With this understanding, we studied the possibility of cooling in two published laser devices. We noticed that the cooling is dominated by optical gain for Ref. 4 and by mirror reflectivity for Ref. 5. These observations thus motivate exquisite engineering of laser devices for enhanced optomechanical cooling.

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Design of Optical Costas Phase Lock Loop in Homodyne Coherent Optical Receiver

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A homodyne coherent optical receiver has the characteristics of high speed and long distance transmission, and optical phase lock loop (OPLL) plays an important part in it. This paper presents a scheme of digital homodyne coherent optical receiver using a field programmable gate array (FPGA) as the central processor. To achieve a wider capture bandwidth and higher tracking precision, a coarse–fine compound control strategy is implemented. The fine tracking loop realizes rapid and precise phase tracking through second-order PI control of an acousto-optic frequency shifter (AOFS). The coarse tracking loop realizes large-scale frequency tracking through first-order PI control of a laser diode controller. Experimental results demonstrate that stable optical phase locking can be achieved with a frequency deviation up to 1 GHz and a Doppler frequency variation rate up to 10 MHz/s. Further experimental investigations are ongoing.

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Autonomous Timekeeping for the Constellation Composed of LEO Satellites and BeiDou-3 Satellites

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The time references established by all major satellite navigation systems, such as BDT and GPST, share a common characteristic: they primarily rely on ground-based control systems for estab-lishment and maintenance. Should the satellite-to-ground link be interrupted, the ground control center malfunction, or the system be compromised for other reasons, the satellite navigation sys-tem would lose contact with the ground. Consequently, it would be unable to determine the time deviation relative to the system's time reference. Without an external time reference for calibra-tion, the onboard time standard may gradually drift away from the navigation system time, ulti-mately rendering the satellite navigation system inoperable. To ensure the normal operation of the satellite navigation system in autonomous mode, it is essential to establish a time reference capa-ble of supporting the independent operation of the satellite navigation system.

Currently, the BeiDou-3 satellite system has achieved full coverage of Ka-band inter-satellite links, enabling autonomous two-way time comparison and bidirectional communication between satellites. In October 2022, a LEO satellite equipped with a high-precision time-frequency system was successfully launched. This system incorporates three different types of high-performance atomic clocks capable of generating time-frequency signals with accuracy levels of E-16 to E-17. Using the 1PPS and 100MHz signals generated by the high-precision time-frequency system as a reference and leveraging inter-satellite link technology, two-way measurements between the LEO satellite and BeiDou-3 satellites have been achieved, allowing for the determination of relative clock offsets between the atomic clocks onboard BeiDou satellites and the high-precision atomic clocks on the LEO satellite.

The LEO satellite is designated as the computational center node. Using the inter-satellite relative clock offsets between BeiDou satellite clocks and the high-precision atomic clocks on the LEO satellite as input, and integrating both LEO and BeiDou-3 satellites, a time scale equation for constellation autonomous timekeeping is established based on classical time scale algorithms. The time scale for constellation autonomous timekeeping is computed using both the KPW algorithm and the fading Kalman algorithm, the autonomous timekeeping scales generated by both algo-rithms are less than 35 ns, with a daily stability better than 4E-15, as shown in Figure 1.

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Integrated dual-wavelength Faraday laser for THz generation

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High-performance dual-frequency lasers are vital for various cutting-edge applications, such as heterodyne laser interferometers, microwave photonics, and quantum precision measurement. Notably, in microwave photonics, dual-frequency lasers, especially those with shared-gain and shared-cavity configurations, enable the generation of highly stable microwave/THz signals in a compact structure. A key advantage of such designs is their intrinsic capability for common-mode noise rejection, which effectively suppresses phase noise induced by environmental fluctuations. This feature renders them particularly suitable for applications demanding low-noise local oscillators, such as atomic gravimeters and atomic clocks.
Common techniques for generating dual-frequency lasers encompass the Zeeman effect, external modulation, and intra-cavity birefringence methods, etc. While these approaches offer structural simplicity and ease of implementation, they generally provide a limited range of achievable frequency differences. Additionally, especially in semiconductor-based gain media, stable dual-frequency emission requires overcoming mode competition effects.
To achieve an integrated dual-frequency diode laser with a large frequency separation, it is essential to establish two distinct transmission windows within the laser cavity. In this context, Faraday anomalous dispersion optical filter (FADOF) is an ideal candidate as its transmission bands are confined close to atomic transitions. Diode lasers incorporating FADOF as a frequency-selective element are referred to as Faraday lasers. Although substantial research has been conducted on single-frequency operation at specific wavelengths, achieving dual-wavelength lasing with terahertz-level separation remains a challenge.
Here, we realize an integrated, dual-wavelength Faraday laser which simultaneously emits at 770 nm and 767 nm, with a frequency difference of approximately 1.7 THz. Through systematic optimization of FADOF operating parameters, the mode competition is suppressed, enabling stable dual-wavelength operation across a broad range of driving currents. Over a 90-minute free-running period without active frequency stabilization, both modes exhibited wavelength drift at the picometer level. Furthermore, by applying modulation transfer spectroscopy (MTS) to lock the 767 nm mode to the 39K D2 transition, the frequency stability of both laser modes was enhanced, indicating strong potential for the development of novel terahertz sources.

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A high-performance optical clock stabilized on 5S-5D two photon transition of rubidium

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Atomic clocks play a crucial role in timekeeping, navigation and positioning. Various microwave clocks, such as cesium beam clocks and hydrogen masers, have been employed in ground-based time and frequency station and Global Navigation Satellite System (GNSS). Optical clocks, with much higher transition frequency, are expected to possess higher stability. Impressive works have demonstrated iodine optical clocks at sea with the long-term stability of <1E-14. The significant advancement indicates the applications of optical clocks under the noisy circumstance. We demonstrate a high-performance optical clock, compatible with 4U chassis, stabilized on the 5S1/2→5D5/2 two photon transition in this work. The stability of the optical clock is comparable to passive hydrogen masers with the average time up to 10000 seconds.

A physics package is carefully designed for the optical clock. Two layers of permalloy are used to shield the magnetic field of earth and current element. Temperature of gas cell is PID-controlled at 360 K by a thermo electric cooler on a heat sink against the cold finger of the gas cell. A C-band fiber DFB laser is converted to near infrared with the wavelength of 778.1 nm to drive the two-photon transition by second harmonic generation in a periodically polarized lithium niobite (PPLN). The blue fluorescence of 420 nm is converted to voltage signal by a photomultiplier (Hamamatsu, H10722-210) which is cooled to 300 K to reduce the thermal noise. The laser power is stabilized by a liquid crystal voltage retarder on a reference voltage. The short-term stability of the optical clock is 3.6E-13, limited by the shot noise, and the long-term stability is 6.0E-15 at 10000 s, limited by ac Stark shift, with the total measurement time of 150000 seconds.

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Allan-Variance-Guided Uncertainty Evaluation for Time-Series Data: Linking Noise Processing and Monte Carlo Methods

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Modern metrology faces a growing need to modernize uncertainty evaluation methods in re-sponse to digital transformation and the increasing prevalence of time-correlated data. Across numerous disciplines including climatology, neuroscience, and structural health monitoring time-series analysis has become central to understanding complex and nonlinear systems that exhibit temporal correlations and scaling behaviors .
This shift highlights the necessity of updating metrological uncertainty approaches to accom-modate correlated data and dynamic measurements. Recent analyses by the European Metrolo-gy Network for Mathematics and Statistics emphasize that training and adoption of simulation-based methods, such as the Monte Carlo approach, remain limited, despite their suitability for non-Gaussian and time-dependent conditions .
In time-and-frequency metrology, where correlations and oscillator noise dominate, the Allan variance serves as a diagnostic tool that quantifies noise type and temporal dependence. In this work, we extend Allan-variance analysis to reveal the distributional effects of noise regimes and demonstrate how these regimes influence uncertainty evaluation. Monte Carlo simulation provides improved estimation across different averaging times by reproducing the full proba-bility distribution of time-correlated data. In contrast, the analytical GUM framework assumes statistical independence and can diverge by up to 10 % in correlated regimes . The two ap-proaches converge in white-noise conditions but diverge significantly in flicker and drift re-gimes. The proposed framework establishes Allan variance as a diagnostic bridge linking sta-bility characterization and uncertainty propagation contributing to the modernization of uncer-tainty analysis and offering a generalizable approach applicable to any time-based measure-ment system.

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Methods and Analysis of Inter-System Time Offset Prediction for GNSS

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This paper proposes a combined Kalman filtering and least squares (K+Q) method to predict GNSS time offsets, a critical factor for navigation accuracy. The Kalman filter is first optimized via grid search to estimate time offsets, and its smoothed output is then used for prediction with a least squares model. Experimental results using BDT/GLONASST data show the method significantly enhances short-term accuracy, reducing the 1-hour prediction RMSE by 41.62% compared to a polynomial model and achieving high-precision (RMSE < 3.9 ns) forecasts within a 3-hour window.

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Progress of PTB’s strontium optical lattice clock Sr3

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Reliable high-performance optical clocks are necessary for optically steered timescales and to prepare the redefinition of the SI second. Thorough characterization of systematic effects and proper control of atom preparation are required to achieve and reproduce an accuracy of few 10^{-18} or below. The PTB-Sr3 lattice clock has been designed for high availability and a target uncertainty of few 10^{-19} in cryogenic operation and few 10^{-18} in room-temperature operation. We present the current status of our efforts to ensure and validate the accuracy and long-term stability of the PTB-Sr3 clock. We report on an external enhancement cavity of the optical lattice, which improves spectral and spatial mode quality of the lattice laser light. Furthermore, we demonstrate characterization of the frequency shift by cold–cold collisions using rapid adiabatic passage (RAP) on the clock transition. Finally, we discuss planned upgrades to the apparatus and challenges on the road to cryogenic operation at 10^{-19} uncertainties.

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Making it Possible - Portable Strontium Lattice Clock

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The abstract details the building and characterising of a portable Sr optical lattice clock, with an expected uncertainty of ~ 5 x 10^-18 and a stability of ~ 10^-16 over 1 second. The system will be compact and robust, while maintaining the stability and uncertainty of a laboratory based system. Through design choices, a single control system, and compact lasers, the project will be realised. Currently, the system is demonstrating red stage cooling after successfully achieving a blue MOT with a novel 448 nm repumping scheme.

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A Galileo-Based Pseudolite System for Improving GNSS Time Transfer

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To improve accurate time synchronization across space geodetic techniques, we propose a ground-based GNSS pseudolite system synchronized with a delay-drift-free timing reference at the Geodetic Observatory Wettzell. The system is designed to mitigate internal delay instabilities in GNSS receiver chains, mainly caused by temperature-dependent effects.

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Broadband optical frequency stability transfer with an AOTF

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We present a new technique to transfer optical frequency stability over > 200 nm without an optical frequency comb. The scheme relies on an unbalanced Mach-Zehnder interferometer including an acousto-optical tunable (AOTF) filter. The AOTF features an inherent broadband operation and an acousto-optical frequency selectivity which respectively allows for frequency transfer over an octave, and virtually to multiple slave lasers. As a proof-of-concept, we transfer the frequency stability of a 780 nm laser reference locked on a Rb cell using saturated absorption method to a slave laser at 960 nm. This setup is the framework for RF sensors based on Rydberg atoms in Rb.

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Recent Developments in Optical Measurement at ROA

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In the last decade, optical clocks have emerged as a significant advancement over traditional microwave frequency standards, achieving unprecedented levels of stability and accuracy. With overall uncertainties reaching the 10-18 to 10-19 range, these optical clocks offer extraordinary performance, demonstrating stabilities better than 10-16 at 1 second. This remarkable progress has paved the way for potential breakthroughs in various scientific fields, including timekeeping, frequency metrology, and fundamental physics, challenging and surpassing the capabilities of previous standards. The continued development of optical clocks promises to redefine precision measurement, with implications for next-generation technologies and applications in both fundamental research and industry.

In anticipation of the redefinition of the SI second , ROA has started developing a strontium (Sr) optical lattice clock, along with planning the installation of optical fiber links for future clock comparisons and the dissemination of time and frequency standards.

In this context, we present the status of our optical lattice clock, which aims to use a promising cooling system for Sr atoms, which uses both Zeeman and Doppler shifts for longitudinal deceleration. A transverse 2D-MOT is included during this process to minimize atom losses by positioning it close to the oven's output. The system's key innovation is using a single array of permanent magnets to generate both the magnetic field for longitudinal deceleration and the gradient for the 2D-MOT.

We also present the status of the frequency distribution over long optical fiber links. Local testing has been conducted over a 250-km fiber link using White Rabbit technology, and preliminary results from a real-time time transfer setup between ROA and Sevilla via Universidad de Cádiz using ADVA Optical Networking's FSP3000 devices over RedIRIS 5.

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Frequency ratio measurements with Al+

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Optical clocks show two orders of magnitude reduction in statistical and systematic frequency uncertainty compared to microwave clocks and a roadmap for a redefinition of the SI second using optical frequency standard(s) has been drawn up. Among several possible candidates Al+ provides a promising optical clock transition, which is insensitive to electric quadrupole and black body radiation shifts and has a lifetime of 20 s. It is already used at different institutes and has shown estimated systematic frequency uncertainties below 2×10−18. This enables frequency ratio comparisons at different institutes with a sufficiently low uncertainty to fulfill the mandatory requirement for the redefinition of the second.
Here we present an Al+ ion clock with a systematic frequency uncertainty of 1.7×10−18. The Al+ is co-trapped with a Ca+ ion to provide laser cooling and state detection of Al+ via quantum logic spectroscopy. By employing electromagnetically-induced transparency cooling on Ca+ during the clock interrogation, we can reduce the motional Doppler shift to −1.69(20)×10−18, independent of the probe time. This allows for long probe times to reduce the frequency instability. The electric field of the light shift can be measured with Ca+ and enables us to determine an induced ac-Stark shift on Al+ of −9.27(1.03)×10−18, which is the dominant uncertainty contribution of the esti-mated systematic frequency uncertainty budget. Measuring the differential polarizability of Al+ at the cooling laser wavelengths of Ca+ could reduce the uncertainty of this shift by one order of magnitude. All other measured systematic frequency uncertainties are well below 1×10−18.
In frequency comparisons against 87Sr we observe a stability of the Al+ ion clock of 5.9×10−16 at 1s for an effective Ramsey interrogation time of 300 ms, which is one of the best ion clock stabil-ities to date. We measure frequency ratios against the 171Yb+ E3 transition with an uncertainty of 6×10−18 for the first time and the ratio shows a good reproducibility over one year of measurement. The frequency ratio against 87Sr is measured with an uncertainty of 4×10−18 and shows a difference at the 10−16 level from a published value. This illustrates the importance of inter-institutional frequency ratio measurement for the redefinition of the second to verify estimated error budgets.

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Comparison of UTC Time Scales of SASO, UME, UzNIM, NIS, AzMI, EMI Using the GNSS Common-View Method

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Under the framework of the Gulf Cooperation Council Standardization Organization's Regional Metrology Organization (GULFMET), A supplementary comparison of UTC time scales has been organized among national metrology institutes from Saudi Arabia, Türkiye, Uzbekistan, Egypt, the United Arab Emirates, and Azerbaijan registered in KCDB under (GULFMET.TF-S2). The exercise employs the GNSS common-view technique to assess the performance and alignment of participating UTC(k) realizations and to reinforce regional traceability.
This initiative represents a cross-RMO collaboration coordinated by GULFMET, bringing to-gether institutes associated with EURAMET, COOMET, and AFRIMETS. The project aims to present the methodology, results, and experience gained from conducting this regional compar-ison, emphasizing the importance of interregional cooperation in strengthening global time and frequency networks.
Alongside the main comparison objectives, the work also includes side goals focused on devel-oping and refining practical techniques for data handling, analysis, and reporting. These activi-ties support continuous improvement of comparison practices within GULFMET and encourage the exchange of know-how between participating institutes. The results to be presented demon-strate both the technical outcomes of the comparison and the progress made toward a more in-tegrated and collaborative time-keeping community.

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Progress Report on the Optical System for the Rubidium Fountain Clock at KRISS

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This work details the development of a highly robust and compact optical system for the KRISS Rb fountain clock, engineered for enhanced long-term stability and reliability. Key innovations include customized, thick aluminum optic boards to ensure stable mechanical alignment, and an auto-aligner system for highly efficient and reproducible fiber coupling. Laser frequency stabilization is managed by a Field-Programmable Gate Array (FPGA) using Modulation Transfer Spectroscopy (MTS) and frequency offset locking. The system employs laser current as the primary actuator, supported by a secondary PID loop using laser temperature to maintain dynamic range. This development represents a significant advancement toward a highly stable, continuously operating, and potentially portable Rb fountain clock.

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Cold atoms coherent population trapping clock based on miniature magneto-optical trap

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With the rapid advancement of laser cooling, cold atom systems have become essential for mod-ern precision measurements due to their exceptional accuracy and stability. However, traditional systems like magneto-optical traps (MOT) are often bulky and complex, limiting their portability. Recent research has focused on miniaturization, with the grating magneto-optical trap (GMOT) offering a promising solution for compact quantum sensors and standards [1-3]. Despite its simplified structure, GMOT still faces challenges such as asymmetry in scattering forces caused by Gaussian incident beams, as well as limitations in size, weight, and power (SWaP) from conventional vacuum systems and coils.
In this study, we developed a miniature GMOT system that incorporates a nested coil chip to re-duce volume and power consumption, and a titanium-sapphire passive chamber for long-term ultra-high vacuum maintenance. Furthermore, we integrated the GMOT system into a coherent population trapping (CPT) clock. High-contrast resonance signals of both Rabi and Ramsey types were observed. These results validate the miniature GMOT system's capability to serve as a physical package for cold-atom-based standards and sensors.
The schematic of the GMOT is depicted in Fig. 1, with insets the grating chip and the nested low-power-consumption coil chip. The grating chip measures 2 cm × 2 cm, while the coil chip measures 3.9 cm × 3.9 cm and consumes ap-proximately 500 mW of power. The vacuum chamber has a volume of $4 \times 4 \times 7$ cm^3 and sustains an ultra-high vacuum below 10^{-8} Torr for over 1,500 hours. As shown in Fig. 2, a CPT signal was generated using the GMOT system with a σ^+/σ^- optical pumping scheme, achieving a continuous-wave (CW) resonance contrast of up to 70%. Subsequent work will involve locking the clock and characterizing its performance.

Progress in the Development of Low-Loss Nanostructured Mirrors for Ultra-Stable Resonators

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An alternative to conventional Bragg mirrors for Fabry-Perot interferometers, are meta-mirrors, which utilize dielectric nano-structured surfaces with sub-wavelength feature sizes and heights. These mirrors can achieve extremely low optical and mechanical losses due to the tailored properties of the structured layer, fabricated from amorphous or crystalline materials. In this contribution we would like to highlight the progress of low-loss meta-mirrors for ultra-stable resonators.

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Research on Atomic Time Algorithm with Temperature Compensation

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This study addresses the problem of frequency drifts in atomic clocks caused by ambient temperature variations, which significantly affect the long-term stability of atomic time (TA). To mitigate these effects, a temperature compensation model was developed, optimized, and applied to atomic time computation. The model was constructed by combining polynomial fitting with physical modeling, based on historical operational data and corresponding temperature records.

Within the traditional ALGOS framework, the conventional polynomial prediction model was replaced with a temperature-compensated prediction model. By correcting nonlinear frequency drifts induced by temperature fluctuations, the proposed approach produced more linear and predictable clock behavior, thereby improving the stability of the computed atomic time.

In the experimental study, five hydrogen maser clocks were subjected to a 1000-hour temperature variation test, during which a controlled temperature disturbance was introduced from 640 hours to 664 hours. A temperature-insensitive atomic clock was used as a reference to compensate for the other clocks. The compensated data were processed using the temperature-compensated prediction algorithm to compute the atomic time.

The results showed that the stability of the compensated atomic time improved by approximately one order of magnitude compared with the uncompensated data. Specifically, the daily stability increased from 1.25E−15 to 9.15E−16. These results confirm that the temperature compensation model suppresses the influence of temperature fluctuations on clock frequency output and significantly enhances the long-term stability of the time scale. The method provides a practical approach for improving the precision and reliability of atomic time computation under varying environmental conditions.

70

Construction of a Compact Two Photon Optical Clock Using Micro-machined Vapour Cells

Miss Eilidh Maclennan[1], Dr Allan McWilliam[1], Miss Abigail Kaye[1], Dr Steven Johnson[1], Professor Paul Griffin[1], Dr James McGilligan[1]
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Poster session 1, April 21, 2026, 15:30 - 17:00

Micro-machined vapour cells have been used to enable the miniaturization of a wide range of atomic sensors, most notably the chip-scale atomic clock (CSAC) [1]. Beyond microwave transitions, optical transitions offer a path toward significantly enhanced stability in compact clock systems. We report on the development of 6mm silicon vapour cells, which have been produced using in-house water-jetting and anodic bonding techniques [2]. These cells consistently exhibit a narrow linewidth of approximately 600kHz for the two-photon transition in rubidium, which is excited with a single 778nm laser. The narrow linewidths and excellent signal-to-noise ratio observed in these vapour cells indicates their suitability as a robust atomic reference for a two-photon optical clock. Building on this foundation, we present a first-generation compact two-photon optical clock that employs one of these vapour cells as its atomic reference. This clock achieves a short-term fractional frequency stability on the order of 10^{-13}. This system represents a key milestone toward realizing a fully chip-scale two-photon optical clock and demonstrates the viability of micro-machined vapor cells as reproducible, high-performance references for the next-generation of precision timing technologies.

72

A new 5G/6G resilient Oscillator to environmental stresses

Mr. Vincent Candelier[1], Mr Anthony Ferreira[1], Mr Diop Malick[1], Mr Kovach Alexander[1]
[1]Rakon

Poster session 2, April 23, 2026, 15:30 - 17:00

A new patent pending mechanical structure of resonator was developed to reduce the environ-mental stresses effect for critical 5G/6G applications. It is pin to pin compatible with the reso-nator used in our 5G standard OCXO families . Its design is presented and explains the unprec-edented performances obtained with these OCXO’s, compared to the same form factor OCXO’s, mainly the acceleration sensitivity (<1e-9/g), the ageing (<3.7e-11/day) and the re-trace effects (<5e-10). These improvements also enhance the holdover performances on short and long term. It is targeting a TIE of 1.5us during a holdover time of 24 Hours without the compensation of the ageing and the use of a GNSS PPS signal or more with their use. All these performances will be presented and compared with the ones of the same OCXO’s but with standard resonators.

74

Advancements in performance of the 171Yb+ ion optical clock at NPL

Mr. Patrick Regan[1], Dr. Alexandra Tofful[1], Mr. Douglas Jones[1], Dr. Thilina Senaviratne[1], Mr. William Bardell[1], Dr. Rachel Godun[1]
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Poster competition, April 21, 2026, 15:30 - 17:00

This poster will present recent improvements to the 171Yb+ optical clock at NPL and discuss how they have led to advancements to performance in terms of accuracy, stability and uptime. We will review redefinition of the second and examine how improvements to the clock system will help us to meet the mandatory criteria for redefinition.

76

Optimizing Long-Term f_rep Stability of a Mode-Locked Laser via Simulation-Based Genetic Algorithm

Mr.先生 Meng Shi[1], Mr. Chuwen Tang[1], Mr. Chen Yang[1], Mr. Shengping Xu[1], Prof. Jianye Zhao[1]
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Poster session 1, April 21, 2026, 15:30 - 17:00

Ensuring the long-term stability of a mode-locked laser's (MLL) repetition rate is critical for precision applications, yet achieving it with digital PID control is challenging due to system nonlinearities and difficult manual tuning. This work introduces an automated optimization framework that employs a simulation-based Genetic Algorithm (GA) to overcome these challenges. A digital twin of the system is first constructed, within which the GA searches for the optimal PID parameters. The core of this approach is a fitness function formulated using the Allan Deviation at 1-second and 1000-second averaging times, which explicitly balances short- and long-term stability. When deployed on hardware, the GA-optimized parameters immediately achieved robust control, suppressing the original long-term frequency drift by over four orders of magnitude. The improvement is demonstrated by a reduction in the Allan Deviation at 1000 seconds from 3e-7 to 6e-12, with no degradation to the short-term phase noise. This method provides a robust, simulation-driven pathway for optimizing laser stability without compromising other performance metrics.

77

Simulation analysis of earth rotation sensing with large area optical time and frequency transfer network

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Poster session 2, April 23, 2026, 15:30 - 17:00

High precision optical fiber time and frequency transfer with wide area network brings new opportunities for astro-geodynamics and earth observing researches. The integration of the metrological, fiber-based infrastructures in the Europe and China, provide the research community with a physical layer over which applications of earth rotation sensing can be built on.
The performance of earth rotation sensing devices based on the Sagnac effect is closely related to the scale factor and sensor orientation. The scale factor is directly proportional to the area enclosed by the device loop. The larger the scale factor, the higher the sensor resolution. High precision optical fiber time and frequency transfer networks provide the necessary conditions for constructing ultra large-scale earth rotation sensing devices based on the Sagnac effect, but also bring difficulties in sensor orientation.
In this work, the Sagnac effect of optical fiber time transfer is reformulated in the geocentric inertial reference system, and the relationship between the Sagnac effect in optical fiber time and frequency transfer and the instantaneous earth rotation vector is obtained, which provides the possibility of earth rotation sensing with the high precision optical fiber time and frequency transfer links.
In order for the simultaneous estimation of earth rotation, the mathematical model of optical fiber time and frequency transfer considering earth rotation is studied. This earth rotation sensing method based on optical fiber time and frequency transfer is validated with the real-like optical fiber routes of China. The influences of optical fiber position accuracy and earth tides are also analysed. The advantages and disadvantages of this method are finally summarized, and the aspects for the following improvement are given.

78

Stochastic Prediction of UT1-UTC to support the decision towards a Continuous UTC

Dr. Giulio Tagliaferro[1], Dr Patrizia Tavella[1]
[1]Bipm

Poster session 2, April 23, 2026, 15:30 - 17:00

The General Conference on Weights and Measures (CGPM) decided in 2022 that the maximum value for the difference (UT1-UTC) will be increased in, or before, 2035. The Consultative Committee for Time and Frequency (CCTF) is therefore working to propose a new extended maximum value as well as the implementation date. In the last years the rotational speed of the Earth has almost continuously increased and today a rotational second is almost as long as the atomic second. If this trend should continue, we will have to remove one second from UTC (negative leap second). As this case never happened before, a large concern is growing in the UTC user communities asking the CCTF to avoid the application of a negative leap second by anticipating the implementation of continuous UTC. To take a decision, it is essential to quantify the likelihood and possible timing of such an event. Earth rotation is difficult to predict: some influencing phenomena, such as atmospheric dynamics, are only partially predictable, while others, such as core–mantle interactions, are today not completely understood and not satisfactorily modelled.
For this reason, we model Earth rotation as a stochastic process. Analysis of the past two centuries of data shows that, on time scales of years to decades, UT1–TAI can be represented as an integrated random walk. By incorporating deterministic effects—tidal friction, Earth tides, and seasonal variations—we derive confidence intervals for future UT1–UTC values using stochastic differential equations. Monte Carlo simulations are then used to estimate the probability of both positive and negative leap second occurrences over the next decade. Results indicate that the probability of a negative leap second becomes non-negligible after 2027, exceeding 30% by 2035. Using data from 1830 to 2025, we validate the model by predicting past values of UT1–TAI and comparing them with historical observations. This validation is performed at 5-year intervals. The back-prediction errors consistently fall within the 3-sigma confidence interval, confirming the reliability of the computed uncertainty estimates.

80

Weak Frequency Jump Detection in Atomic Clocks Based on a Dual-Filter Difference Algorithm

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Poster session 1, April 21, 2026, 15:30 - 17:00

This paper presents a dual-filter difference algorithm for detecting weak frequency jumps in atomic clocks, especially cesium clocks where white frequency noise (~10^{-11}) can obscure small jumps. The method employs two Kalman filters with different observation noise covariance values (R):
A small-R filter for fast response and real-time frequency estimation.
A large-R filter for smooth frequency prediction.
The difference between their outputs forms a differential signal that amplifies frequency jumps. Under normal conditions, this differential follows a Gaussian distribution; after a jump, it deviates significantly before the large-R filter converges. By applying fixed-window integration to this differential, weak frequency jumps can be effectively detected.
Experiments using a 5071A cesium clock referenced to UTC(NTSC) verified the method's effectiveness. A frequency jump of 5×10^{-12} at 1800 seconds was successfully detected, demonstrating improved sensitivity compared to traditional single-filter approaches.

82

Broadband Dual-Comb Calibration of Reference Gas Cells for High-Precision Astronomical Spectrographs

Dr. Francesco Canella[1], Prof. Alessio Gambetta[2], Mr. Niccolò Salvatore Barberio[2], Mr. Antonio Caruso[2], Mr. Riccardo Ciantini[3], Dr. Stefania Stefani[4], Dr. Lorenzo Cabona[5], Prof. Riccardo Claudi[6,7], Prof. Paolo Laporta[2], Dr. Gianluca Galzerano[1]
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Poster session 2, April 23, 2026, 15:30 - 17:00

Dual-comb spectroscopy is nowadays a well-established high-precision spectroscopic technique. Recently, many applications based on novel GHz-repetition rate optical frequency combs have been developed, allowing fast measurements and wide bandwidth. Applications also include astronomy, where the calibration of high-precision spectrographs is essential for many applications, such as exoplanet search. Simple approaches that guarantee good accuracy in spectrograph calibration can be used as an alternative to more complicated Astrocombs. In this work, we demonstrate the calibration of two reference gas cells realized for the INAF's Galileo Italian National Telescope, installed at La Palma (Spain). Exploiting a dual-comb spectroscopy setup, we calibrated the spectral lines of acetylene, methane, and ammonia in the spectral region between 1000 and 2300 nm, with a resolution of 1 GHz, and an acquisition time of ~100 µs per measurement. The experiment is based on two identical 1560-nm mode-locked lasers with a repetition rate of ~1 GHz. Pulses are amplified, compressed, and spectrally broadened in new-generation Ta_2O_5 waveguides before reaching the gas cells. A post-processing software allows an SNR improvement while keeping the lasers free-running.

85

Space Qualification of SAW Filters Based on POI Technology

Dr. Kaoutar Zeljami[1], Dr Aintzane Lujambio[1], Mr Mario Rueda[1], Dr Sylvain Ballandras[2], Mr. Thierry Laroche[2], Dr Olivier Vendier[3], Ms Paula Marin Banque[3]
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Poster session 1, April 21, 2026, 15:30 - 17:00

This work presents the qualification of L-band POI-based SAW filters in hermetic packaging, carried out by ALTER TECHNOLOGY within the framework of the HOMEMADE project. The device, based on a POI substrate developed by SOITEC, is designed for a generic GPS filter operating in L-band. The objective is to validate the reliability of this component for space applications, aiming to achieve Technology Readiness Level 7 (TRL7).
The qualification campaign included initially screening phase followed by temperature cycling, life tests, and mechanical testing to ensure robustness and long-term stability, complemented by a constructional analysis to assess structural integrity. In addition, radiation tests were performed to demonstrate the device's tolerance to the space environment, covering both Total Ionizing Dose (TID) and Displacement Damage (DD) effects.

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Timing transfer with Repeater Laser Station over optical fiber

Mr. Haniffe Mouhamad[1], Mr Fabrice Wiotte[1], Mr Etienne Cantin[1], Mrs Anne Amy-Klein[1], Mr Christian Chardonnet[1], Mr Olivier Lopez[1]
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Poster session 2, April 23, 2026, 15:30 - 17:00

With the development of optical fiber links, which enables the dissemination of an optical fre-quency standard on continental distances, efforts are ongoing for more than ten years to distrib-ute metrological timing signals. Some developments have reached maturity and offer interest-ing performance, such as White Rabbit and ELSTAB . Investigations with SATRE modems and optical modems have also shown potentials for high-performance timing dissemination up to the picosecond instability.
The experimental development shown here is part of an ongoing effort to achieve syn-chronization between remote users on the REFIMEVE network, and dissemination to users of high-performance time signals from LTE, the French NMI for time and frequency metrology, for a wide range of applications.
In our experimental setup, two Repeater Laser Stations (RLS) are connected by 75 km of fiber spools, as shown in Figure 1. The RLS A is phase-locked to the REFIMEVE optical signal, and the RLS B is phase-locked to RLS A using active noise correction (ANC) to correct for phase noise accumulated in the fiber. Each station is connected to a time modem to achieve two-way transfer. The timing signal is modulated on an RF carrier with a pseudo-random noise (PRN) code, which in turn modulates the phase of the optical carrier. On reception, the RF modulation is extracted using the beatnote between the remote and local lasers. The spectral occupancy and detection of the modulation is constrained by signals intended for ANC. A limi-tation studied in this paper is the variation of the beatnote level due to polarization effects, lead-ing to AM/PM conversion in the demodulation electronics. To mitigate these effects, we stabi-lized the power level before demodulation. Once demodulated and detected, the timing signal, which is encoded by a PRN sequence, is synchronized to the local timing. Measurement is final-ly implemented in an FPGA using Digital Dual Mixer Time Difference. Preliminary results show an instability of the order of 20 ps at 1-s averaging time for the code transfer to station B, and the instability in a two-way configuration is less than one picosecond at 1 s on the RF carri-er phase, and long-term instability at a level of 100 ps. This is promising but remains to be con-firmed on a real link with a complete prototype.

92

Novel Time and Frequency Transfer System Based on DORT Technology

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Poster competition, April 21, 2026, 15:30 - 17:00

The abstract presents a novel technique to transfer frequency and time, based on a distance measurement technology named DORT System. A brief introduction to this technology, followed by an explanation of the experimental frequency transfer setup are provided.

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High Availability Yb Optical Lattice Clocks at NPL

Dr. Thomas Easton[1], Miss Roxanne Siadat[1,2], Dr Maxime Favier[1], Mr Ben Allen[1], Dr Shirin Hussein[1], Mr Max Tamussino[1], Dr Ian Hill[1]
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Poster session 1, April 21, 2026, 15:30 - 17:00

Improved frequency standards are needed to evaluate and calibrate new technology emerging from the development of quantum industry. Optical lattice clocks (OLCs) are an excellent candidate to meet this challenge. Compared to ion clocks, OLCs provide improved stability, while having uncertainties demonstrated at the 10-18 level and below. So far, typical OLCs operate as experiments rather than services, and there is a clear need for increased availability and connectivity to consumers. To this end, we are developing new Yb optical lattice clocks with this emphasis. The new Yb lattice clocks will provide a high-performance optical frequency reference with traceability to the SI, underpinning a new quantum test & evaluation facility. The facility will serve industrial and academic partners both locally and remotely via NPL's growing UK optical fibre network and the connected European networks.
To attain high Signal availability, we are standardising a clock design and increasing the technology readiness level of the various subsystems. These include a laser stabilisation subsystem based on a dual-axis cubic cavity; rack mounted laser distribution modules; and an experimental control subsystem based on the ARTIQ infrastructure with complementary RFSoC hardware, allowing for reconfigurable operation of the clock with a high degree of autonomy. These are all being engineered for resilience without compromising on performance, as we aim for a fractional frequency inaccuracy of ~1×10-18.
We will present the design and early outputs from the first Yb OLC at NPL. Aided by our standardised approach we aim to deploy a second system in the near future. This will add a layer of redundancy to the clock's operation, increase measurement confidence, and allow us to operate in zero-dead-time configuration for extended optical coherence. Adding Yb to the existing ensemble of optical clocks at NPL, which includes Sr and Yb+, will allow more frequency ratio measurements. Finally, our high availability Yb lattice clocks will be able to regularly contribute to TAI, alongside existing optical clocks at NPL, supporting the case for a redefinition of the SI second.

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Ruggedized and Hermetic Laser Module for Space-Qualified Ultra-Low-Noise GHz-Repetition-Rate Frequency Combs

Dr. Andrea Pertoldi[1], Maria Milanova[1], Dr Oguzhan Kara[1], Dr Benjamin Rudin[1], Dr Florian Emaury[1], Julien Rouvinet[2], Jean-Luc Helfer[2], Simon Hayoz[2], Lauriane Karlen[2], Christopher Bonzon[2]
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Poster session 1, April 21, 2026, 15:30 - 17:00

This work presents a fully hermetic, vibration-tolerant package for GHz repetition-rate optical frequency combs, designed for deployment in space environments. The module isolates the laser from pressure and temperature fluctuations, enabling stable operation from high vacuum to atmospheric pressure, with hermeticity down to 10e-9 mbar.L/s and long-term drift below tens of kHz over several years. The housing uses a Kovar body, indium sealing, and flexure mounting for thermal and mechanical stability, withstanding -40 to +60 °C temperature swings and launch-level shock and vibration. By combining robust packaging with ultra-low-noise mode-locked lasers, this approach enables compact, space-compatible frequency references suitable for satellite-based optical clocks, time-transfer networks, and ultra-low-noise microwave generation.

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Integration of new technologies into Paul trap based clock experiments

Mr. Markus Kromrey[1], Fatemeh Salahshoori[1], Leonie Vieler[4], Max Glantschnig[5], Klaus Kiendlhofer[5], Suat Icli[1], Carl F. Grimpe[1], Guochun Du[1], Atasi Chatterjee[1], Elena Jordan[1], Tanja E. Mehlstäubler[1,2,3]
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Poster session 2, April 23, 2026, 15:30 - 17:00

We want to present our work towards a portable optical clock. This includes a Paul trap designed to trap multiple ensembles of ions, the use of a compact setup for the detection of fluorescence light with SPADs (single photon avalanche diodes), as well as the inclusion of nanophotonic structures to shape and deliver the light that is used in the clock experiment.

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The preliminary evaluation of the NIM-Yb1 Ion Optical Clock

Dr. Shaoyang Dai[1,2], Chaowei Wang[3], Dr. Yani Zuo[1,2], Dr. Shiying Cao[1,2], Dr. Kun Liu[1,2], Weiliang Chen[1,2], Dr. Fasong Zheng[1,2], Dr. Fang Fang[1,2]
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Poster session 1, April 21, 2026, 15:30 - 17:00

Optical atomic clocks are regarded as a leading candidate for the redefinition of the second in the International System of Units (SI). Based on an endcap ion trap, the National Institute of Metrology (NIM) of China has developed a 171Yb+ optical ion clock. An ultra-high vacuum environment and a highly reliable laser system have been established, incorporating a 369.5 nm third-harmonic generation fiber laser[S. Y. Dai, "The research of 369.5 nm laser stabilizing method and its influence on ytterbium ion optical clock", AIP Advances, 15, 075132, 2025.], as well as 760 nm and 935 nm distributed feedback (DFB) lasers, enabling long-term stable operation. The 435 and 467 nm lasesr have been locked to 100 mm and 200 mm ULE cavities, respectively. Both the electric quadrupole (E2) and electric octupole (E3) clock transitions have been observed and locked in closed loop. Time-interleaved self-comparison results demonstrate in-loop stabilities of 1.4E-14 (τ/s)-1/2 and 1.7E-15 (τ/s)-1/2 for the E2 and E3 transitions, respectively. By measuring the frequency change of the magnetic sub-level of the E2 transition, the uncertainty of the second-order Zeeman shift was evaluated to be 2E-19. The temperature of the ion trap was measured using an infrared thermal imager, and the uncertainty of the blackbody radiation frequency shift reached 2.2E-18. The total uncertainty from the major uncertainty is evaluated to be 3.5E-18. Utilizing a cold atomic fountain clock ensemble, a rapid absolute frequency measurement of the E3 transition has been achieved. The measured absolute frequency is 642,121,496,772,645.23 Hz, with a measurement uncertainty of 2.7E-16.

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Research on a High-Precision Microwave Two-Way Time Transfer Method Based on Noncommensurate Sampling

Miss Guoying Wu[1]
[1]Casic

Poster session 1, April 21, 2026, 15:30 - 17:00

This work investigates a high-precision microwave two-way time transfer (TWTT) method based on noncommensurate sampling. The study analyzes how commensurate and noncommensurate sampling affect the pseudorandom noise (PN) code correlation peak, revealing that noncommensurate sampling effectively mitigates staircase and multivalued effects without increasing the sampling rate. Experimental validation on a software-defined radio (SDR) platform demonstrates that noncommensurate sampling achieves continuous clock offset variation and enhances temporal resolution to the 1 ns level. The results provide practical guidelines for sampling-rate design in high-precision time synchronization systems.

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Dynamic microwave time synchronization tracking algorithm based on variational Bayesian AKF

Dr. Yan Cheng[1], Dr. Guoying Wu[1], Dr. Haifeng Wang[1], Prof. Xueyun Wang[1], Dr. Wenzhe Yang[1], Dr. Hang Yi[1], Prof. Shengkang Zhang[1], Prof. Jun Ge[1]
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Poster session 2, April 23, 2026, 15:30 - 17:00

In dynamic networking systems such as unmanned aerial vehicle (UAV) systems, the real-time maintenance of time synchronization is the fundamental prerequisite for establishing the dynamic collaborative system. However, the current high-precision time synchronization systems are suitable for working in static conditions. In challenging dynamic conditions, the receiver of the time synchronization systems is difficult to work . Accordingly, it is important to enhance the performance of the time-synchronized receiver in dynamic platforms. The tracking loop is the critical part of the time-synchronized receiver, which performs demodulation and despreading of the time-synchronization signal. In dynamic conditions, the tracking loop is susceptible to losing lock. To enhance the stability of the tracking loop for time synchronization in dynamic conditions, an AQ-VBAKF (adaptive Qk -based variational Bayesian adaptive Kalman filtering) based tracking loop is proposed for the high-precision time-synchronized receiver. The proposed tracking algorithm employs the variational Bayesian algorithm to adjust the measurement noise covariance and apply the adaptive factor to adjust the process noise covariance in the tracking loop filter. Therefore, the proposed tracking loop is capable of adapting to the dynamic variations of the input time-synchronized signal. According to the experimental results, in the dynamic scenarios with variable acceleration, the AQ-VBAKF tracking algorithm exhibits its superiority in terms of stability compared with the existing time-synchronized tracking loop.

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Simple and Highly Precise Frequency Replication from Mode-Locked Frequency Comb to Electro-Optic Comb

Dr. Mayuri Nakagawa[1], Mr. Kota Nishiyama[1,2], Mr. Kohjun Koshiji[1], Dr. Hiromitsu Imai[2], Dr. Kenichi Hitachi[2], Dr. Katsuya Oguri[2], Ms. Rie Hayashi[1]
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Poster session 1, April 21, 2026, 15:30 - 17:00

Optical frequency combs (OFCs) with high repetition frequency (f_rep) enable fast and sensitive measurements using broadband pulsed features, and allow a single frequency mode to be extracted by just using an optical filter, which can be used as a frequency-selectable optical reference for astro-comb, metrology, and other high-precision light sources. Especially, frequency combs generated by electro-optic modulation (EO combs) are promising light sources for their flexible f_rep, which equals the modulation frequency by their electrical input and can exceed 10 GHz. EO combs have also attracted increasing attention as light sources for optical communications, because they can reduce the required number of oscillators. Nevertheless, the frequency stabilization for EO combs is not as developed as for mode-locked (ML) lasers, owing to their principle of comb generation. In this work, we demonstrate an extremely simple and high-performance system to replicate the precision of a mode-lock based frequency comb to an EO comb.
The main difficulty in achieving high-precision EO combs is frequency control, owing to a large phase noise in f_rep before frequency control, and the elaborate system for carrier-envelope offset frequency (f_CEO) detection. Therefore, we aim to use a modulation frequency that is stabilized prior to generating the EO comb, by using a ML laser locked to high-precision optical reference. To reduce the required frequency control and simplify the system, the integer multiple of frep in the stabilized ML laser is detected using a high-speed photodetector (PD) and an electrical filter for the modulation, instead of using beat detections to control the EO comb. The frequency replication is tested with an ML laser locked by f_CEO=10 MHz and f_rep=100 MHz. The narrow-band filter with a center frequency of 10 GHz is used to extract 100f_rep=10 GHz as the electrical input of EO modulation. Consequently, the f_rep of the EO comb becomes 10 GHz. The frep stability of the EO-comb evaluated by Allan deviation corresponds reasonably well with that of the ML laser, and no deterioration is observed. This work provides the technique for realization of practical high repetition and high precision OFCs.

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Simulation of the radio frequency field of the 199Hg+ ion microwave clock and cooling with different buffer gases

Mr. Shilong Feng, Dr. Xiaobo Xue[1], Dr. Nuanrang Wang[1], Dr. Yunjia Wang[1], Mr. Yan Pan[1], Mr. Shengkang Zhang[1]
[1]Beijing Institute of Radio Metrology and Measurement

Poster session 2, April 23, 2026, 15:30 - 17:00

When the ^{199}Hg+ microwave clock is exposed to a radio frequency field, its amplitude and frequency will inevitably experience minor fluctuations. This paper uses COMSOL to
simulate the minor changes in the amplitude and frequency of the radio frequency field, as well as the ion values and lifetimes within the quadrupole trap under different buffer gas conditions. The simulation results are highly consistent with the experimental data.

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Carrier-phase TWSTFT between BIRMM and NIM by Using an Integrated Frequency Converter

Dr. Wenzhe Yang[1], Mr. Haifeng Wang[1], Prof. Xueyun Wang[1], Mr. Hang Yi[1], Prof. Shengkang Zhang[1], Dr. Chao Zhou
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To achieve long-distance high-precision time synchronization, this study has developed a carri-er-phase two-way satellite time and frequency transfer system based on a newly designed inte-grated frequency converter. The principle of carrier-phase TWSTFT has been widely verified . A carrier-phase TWSTFT link has been established between BIRMM and NIM. The core components of the system include a self-developed modem , an integrated frequency converter, and a set of fixed antennas and a set of portable antennas.
Compared with the discrete frequency conversion devices in traditional satellite communications, the integrated frequency conversion design adopted in this system highly integrates the L-band up and down converters, power amplifiers, and low-noise amplifiers, not only effectively ensuring the stability during the frequency conversion process but also significantly reducing the error introduced by the DDS frequency word in the system's phase-locked loop. Experimental results show that under a working environment of 0 to 50°C, its additional frequency instability is better than 8×10^{-14}@1s.
From October 23 to 24, 2025, relying on the reference source of the Chinese Standard Time (CST) system, a 24-hour time deviation measurement between CST (BIRM) and CST (NIM) was carried out. Taking the measurement results of the CST optical fiber link as the reference, the time difference between CST(BIRM) and CST(NIM) of Carrier-phase TWSTFT and CST optical fiber link are shown in the figure: the red curve represents the measurement results of TW Carrier(with about 1 hour of interruption), and the blue curve represents the measurement results of CST optical fiber link. The X-axis represents time, with the unit of "seconds within a day", and the data points exceeding 86400 seconds are obtained by adding 86400 to the "seconds within a day" of October 24. Statistical results of double-difference data show that the mean value is 0.16ns, peak-to-peak value within 24 hours is 0.23ns, and the jitter (1-σ) is 61ps.

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A fixed parameter prediction method for hydrogen atomic clocks based on WOA-GRU

Mr. Ang Li[1], Mr Tiezhonng Zhou[1], Mr Xiaobo Xue[1], Mr Dehao Chen[1], Mr Yabei Su[1]
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The operating state of a hydrogen atomic clock is determined by both its internal parame-ters and the external environment. Currently, providing a stable environment with consistent temperature and humidity is relatively easy to achieve. Therefore, the internal parameters play a crucial role in ensuring the stability of the hydrogen atomic clock's operating state. As the hydrogen atomic clock continues to operate, the values of some adjustable parameters may fall outside the normal range, affecting its operating state. With the rapid development of science and technology, machine learning has become an indispensable part of various scientific re-search endeavors. Although machine learning has been applied in the field of atomic clocks, it is not deeply involved. Instead, it is more often used for analysis through machine learning methods.
To ensure that the internal parameters of the atomic clock remain within the normal range and are relatively stable, this paper proposes a fixed parameter prediction method for hydrogen atomic clocks based on a combination of the Whale Optimization Algorithm (WOA) and the Gated Recurrent Unit (GRU) network. Specifically, based on the traditional machine learning framework, this method combines the global optimization capability of WOA with the tem-poral modeling advantages of GRU to achieve fixed value prediction of the adjustable internal parameters of the hydrogen atomic clock. Simulation experiments show that the prediction ef-fect is good.

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Towards Multi-Frequency GNSS PPP Timing: A UTC(k)-Traceable DCB Estimation Method and Its Application

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[1]Beihang University

Poster session 2, April 23, 2026, 15:30 - 17:00

Global Navigation Satellite Systems (GNSS) serve as a cost-effective, wide-coverage, and high-precision method for time and frequency transfer. Among various techniques, Precise Point Posi-tioning (PPP) has emerged as the mainstream technique for high-precision GNSS time transfer. However, existing GNSS timing services are constrained by their reliance on specific frequency combinations and a lack satellite Differential Code Bias (DCB) products that support multi-frequency PPP timing. The public available DCB products from the Internal GNSS Service (IGS) are inconsistent with the hardware calibrations employed by timing laboratories, rendering them unsuitable or inapplicable for direct use in PPP timing.
To address the demand for multi-frequency PPP timing, this paper proposes a satellite and re-ceiver DCB estimation method that is traceable to UTC(k). We analyze the estimated DCB prod-ucts and examine the BDS/Galileo/GPS hardware calibrations across multiple timing laboratories. Furthermore, the study investigates the application and performance of these newly defined DCB products in PPP timing. Experiments were conducted using observation data from 236 MGEX stations and 9 timing laboratories. The results demonstrate significant improvements in DCB estimation and PPP timing.
Beyond enabling multi-frequency GNSS PPP one-way timing services, this study also presents a novel approach for the remote relative calibration of GNSS receiver hardware delays.

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Highly charged ion spectroscopy for metrology and funda-mental physics studies

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Highly charged ions (HCI) are promising candidates for improved optical atomic clocks. Their high charge leads to a stronger confinement of the remaining electrons, making them less suscep-tible to external field shifts. Furthermore, HCI feature interesting properties for fundamental physics research such as enhanced relativistic and QED effects, as well as a larger sensitivity to variation of fundamental constants and dark matter candidates. Thus, HCI spectroscopy can be used for precise tests of the standard model.
In the past our team developed an experimental setup to confine HCI with a co-trapped Be+ ion for sympathetic cooling and quantum logic readout in a cryogenic linear Paul trap. This allowed us to measure frequency ratios of isotopes of Ar13+ as well as Ca14+ to the other optical clocks at PTB with uncertainties in the 10-16 range, limited by the statistical uncertainty, while all systemat-ic effects have been characterized to a level below 2×10-17.
The flexibility of the quantum logic spectroscopy approach allows us to easily change the clock species. Therefore, we have moved towards a new spectroscopy ion species in Ni12+, featuring a long lived 3P0 excited state with 20 s lifetime, which allows for longer interrogation times and improved statistical uncertainty. Here, we report on the initial transition search including the techniques employed to find this transition with an 8 mHz natural linewidth in an uncertainty range spanning multiple 100 GHz and show the first results of coherent Ni12+ spectroscopy.
Furthermore, a pathway to using Ni12+ as an optical clock is shown and an outlook towards the expected spectroscopic uncertainty is presented employing emerging techniques like entangle-ment or dynamical decoupling.

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White Rabbit Time and Frequency Distribution with Picosecond Accuracy in a Deployed Quantum Testbed

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We report a White Rabbit-based multi-node time and frequency distribution architecture integrating a novel in-situ calibration method for chromatic dispersion-induced delay asymmetry. The scheme enables picosecond–level time synchronization by locally calibrating multiple remote nodes. Field measurements demonstrate that time synchronization accuracy of 18±126 ps at 95% confidence level over 80 km of deployed fiber link has been achieved, with uncertainty estimated from all systematic and statistical sources.

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A Ground Clock at the 1E-16 Level

Mr. Ludwig Blümel[1], Dr. Dominik Bourgund[1], Markus Oswald[2], Niklas Röder[2], Dr. Alexander Friedrich[2], Thomas Zechel[1], Dr. Thilo Schuldt[2], Prof. Dr. Claus Braxmaier[2,3]
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Core technologies like global satellite navigation systems rely on highly stable clocks. In our contribution to EFTF 2026 we present our concept for a European ground-based optical clock with a stability on the 1E-16 level and first experimental results.

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High-Precision Free-Space Optical Frequency Dissemination Across a Sea Link

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We have established and implemented two free-space time-frequency transfer links in the Hangzhou Bay of China, with transmission distances of 5.8 km and 58 km, respectively. By utilizing an acquisition, tracking, and pointing (ATP) system, the spatial beam drift caused by atmospheric turbulence is effectively suppressed, thereby improving the coupling efficiency of received light from free-space to optical fibers. Through two-way optical frequency comparison tests, the frequency instability of both free-space links has been measured to reach 2.8e-19 at 100 s. The demonstrated robustness of optical two-way optical frequency transfer is encouraging for future femtosecond clock synchronization over very long distance ground-to-air free-space paths.

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Three-Month-Long Parallel Distribution of UTC(NIM) Time Scale and Strontium Optical Lattice Frequency Standard at NIM over a Single Fiber Communication Channel

Dr. Hanxu Wu[1], Dr. Xiaoming Zhang[2], Dr. Haifeng Wang[1], Dr. Zhengsen Jia[3], Dr. Peihao Cheng[1], Dr. Hai Xu[3], Dr. Li Song[1,4], Dr. Xinyi Chen[1], Dr. Yang Fu[1], Dr. Weinan Zhao[1], Dr. Yameng Zhai[1], Dr. Fan Huang[1], Dr. Haonan Li[1], Dr. Yuzhuo Wang[3], Dr. Yige Lin[3], Dr. Aimin Zhang[3], Dr. Jun Ge[1], Dr. Shengkang Zhang[1], Dr. Honglei Yang[1]

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Accurate and stable time and frequency distribution and regeneration play an important role in diverse fields ranging from advanced scientific research to industrial applications. Here, we present parallel transfer and regeneration of UTC(NIM) time scale and a coherent optical carrier referenced to Strontium (Sr) optical lattice frequency standard over a single fiber communication channel from National Institute of Metrology (NIM) to Beijing Institute of Radio Metrology and Measurement (BIRMM). At NIM, the 10-MHz frequency signal and 1 PPS signal referenced to UTC(NIM) are imprinted on a 1.55-μm coherent optical frequency carrier referenced to Sr optical frequency standard maintained at NIM by direct-sequence spread spectrum modulation. The synchronization of the coherent optical frequency carrier is achieved by optical phase locking in a reciprocal bi-directional fiber link, while the regeneration of UTC(NIM) time scale at BIRMM is realized by demodulating pseudo-random binary sequences in homebuilt modems and disciplining a phase and frequency offset generator fed by a hydrogen maser. A measurement campaign was conducted over a 68-km metropolitan fiber link for three months, and the regenerated UTC(NIM) time scale was compared with the UTC(BIRMM) time scale and further verified against UTCr data. The time scale regeneration accuracy reached sub-nanosecond level. This method should be applicable to future ground-based optical time scale distribution.

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Preliminary Research on the Steering Techniques of Optically-Pumped Cesium Atomic Clock

Dr. Hongqiang Du[1], Dr. Jianjun Gong[1], Dr. Wenjun Wu, Dr. Shaowu Dong
[1]National Time Service Center

Poster session 2, April 23, 2026, 15:30 - 17:00

Four optically pumped cesium clocks form a time-keeping system. Given the constraint of a limited number of atomic clocks, the steered time signal must be maintained within a specified time deviation range relative to UTC(NTSC) as closely as possible. To achieve this goal, adaptive improvements to the steering algorithm are necessary. Based on the characteristics of random walk noise in optically pumped cesium atomic clocks, and the constraint of a limited number of atomic clocks, an exponential smoothing algorithm has been introduced. Experimental results show that the deviation between the steered time signal and UTC(NTSC) remains within ± 8 ns. At the same time, the frequency stability of the steered time signal has also been improved for both one-day and five-day periods.

Status report of the activities in the OptAsia collaboration

Dr. Takumi Kobayashi[1], Dai-Hyuk Yu[2], Hyun Gyung Lee[2], Joon Hyo Rhee[2], Gyeong Won Choi[2], Young Kyu Lee[2], Huidong Kim[2], Chang Yong Park[2], Dohyeon Kwon[2], Myoung-Sun Heo[2], Won-Kyu Lee[2], Nils Nemitz[3], Mads Tønnes[3], Hidekazu Hachisu[3], Nozomi Ohtsubo[3], Yuto Kozuki[3], Tetsuya Ido[3], Shilpa Manandhar[4], In Cheol Seo[4], Yan Ying Liu[4], Yung Chuen Tan[4], Yusong Meng[4], Shintaro Nagase[1], Takehiko Tanabe[1], Akiko Nishiyama[1], Akio Kawasaki[1], Masami Yasuda[1]
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Aimed at regular optical clock comparisons based on the global navigation satellite systems (GNSSs), the OptAsia international collaboration is formed among research institutes in East Asia: KRISS (Korea), NICT (Japan), NMC (Singapore), and NMIJ (Japan). In this presentation, we present recent results of the frequency comparisons obtained by the automated analysis and future perspectives including the use of some other GNSS software solutions.

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Adaptive Atomic Clock Difference Prediction Algorithm Based on ARIMA-BiLSTM Model

Dr. Yiheng Wang[1,2], Haibo Yuan[1,2], Dr. Zongyuan Li, Hong Zhang[1,3]
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Poster session 1, April 21, 2026, 15:30 - 17:00

As timekeeping systems evolve from centralized single-node systems to distributed multi-node systems, various ground-based and space-based atomic clock resources are being widely deployed, making the integration of different atomic clock types an emerging trend. Different clock types (e.g., hydrogen masers, cesium clocks, rubidium clocks) exhibit markedly different noise spectrum and frequency-drift behaviors due to differing physical mechanisms, which makes it difficult for traditional single-model predictors to balance universality and high accuracy. To address this, we propose an adaptive ARIMA-BiLSTM hybrid prediction algorithm for heterogeneous atomic clocks.

The algorithm constructs a resilient adaptive hybrid framework: the ARIMA model fits linear trends and periodic components in the atomic clock data, while the BiLSTM model captures bidirectional nonlinear temporal dependencies and complex noise, thereby simultaneously characterizing both short-term sudden changes and long-term trends in the data. The innovation lies in an online adjustment mechanism based on residual statistics and real-time performance metrics. This mechanism dynamically optimizes the combination weights of ARIMA and BiLSTM, sliding-window length, and regularization parameters during operation, enabling intelligent adaptation to the dynamic characteristics of different atomic clocks. The computational workflow is: first, perform differencing and pre-processing of the clock difference data and produce an initial prediction using ARIMA; second, feed ARIMA residuals into the BiLSTM for bidirectional nonlinear modeling with online hyperparameter tuning; finally, fuse the ARIMA and BiLSTM predictions according to the adaptive weight strategy to generate the final atomic clock difference forecast.

Experimental results show that, compared with single-model approaches, the hybrid model significantly reduces mean squared error (MSE) and mean absolute error (MAE) in short to mid-term forecasts, and demonstrates strong prediction accuracy and adaptability across clocks with differing characteristics such as hydrogen clocks and cesium clocks. This resilient hybrid model offers a general solution that combines accuracy and robustness for clock difference predicting of heterogeneous atomic clocks, and can provide more reliable data support for high-precision timekeeping, navigation synchronization, and next-generation multi-node timekeeping systems.

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Stable RF Transmission Based on Optical Frequency Shift

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High-precision frequency transmission plays a crucial role in navigation, geodesy and long-distance-distributed radio telescopes. As a low-noise frequency reference, optical carrier has demonstrated sufficient superiority in this field. Actually, the regenerated radio frequency(RF) is frequently required for the majority of remote users. Most of these systems adopt intensity modulation method, where the signal-to-noise ratio(SNR) of the modulated sideband is limited compared with the optical carrier. Thus, taking full advantage of the high SNR of optical carrier to achieve RF transmission has become a crucial issue. Here we present a high stable RF transmission scheme by beating two optical carriers originating from one ultra-stable laser. As illustrated in Fig. 1, the targeted RF signal is served as a reference for frequency shift of the upper optical carrier. The two optical carriers transmit for a round trip in the fiber link, and phase pre-compensation is accomplished by the acousto-optic modulator(AOM)1 and AOM2. There is no influence of backward Rayleigh scattering due to the proper frequency shift of AOM3 and AOM4. The preliminary simulation experiment has been demonstrated, and the root-mean-square (RMS) phase jitter of the 4 GHz RF signal at remote site is close to 0.001 rad. This approach presents significant potential for establishing high stable RF transmission systems in long-haul fiber-optic link.

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A High-Precision Controllable-Delay Repeater System for GNSS Receiver Testing

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Global Navigation Satellite System (GNSS) receiver performance testing, particularly the eval-uation of timing delay accuracy and stability under real signal conditions, is critical for ensuring receiver reliability in high-precision positioning and timing applications. This paper proposes and experimentally validates a high-quality GNSS signal generation and precision time-delay control system based on a real-time repeater architecture. The system is capable of maintaining signal integrity and stability during real-time signal repeating while enabling nanosecond-level precision control over the time delay introduced in the repeating link.

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A Rubidium 2-photon Frequency Reference using Fibre Components

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The rubidium 2-photon transition has been used by a large number of groups as an optical frequency reference using a vapor of thermal atoms, the primary draw being their simplicity for use in portable systems . Producing compact and low power systems using stable lasers required the use of telecoms lasers, which been developed to be widely available and robust. The rubidium 2-photon clock transition at 778.105 nm can be produced by frequency doubling a telecoms laser at 1556 nm. We present an all-fibre component optical system for probing the clock tran-sition in rubidium, for the future development of a rugged and transportable frequency reference.

Furthermore, we present the optimization of the measurement parameters for these systems. Optimizing the short-term stability of the frequency measurement is critical to producing a precise clock. The 2-photon transition decays via a 420 nm transitions, the blue fluorescence is measured while the optical frequency is scanned over the transition to measure the linewidth. This indication of short-term stability the signal-to-noise can be used to optimize a range of parameters; namely the cell temperature, optical input power, and the focusing strength of the light into the thermal vapor cell.

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Phase noise measurement of optical amplifiers

Dr Damien Teyssieux[1,3,4,5], Dr Martin Callejo[1], Dr Jacques Millo[1,3,4,5], Prof Enrico Rubiola[1,2,3,4,5], Dr Rodolphe Boudot[1,3,4,5]
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Poster session 1, April 21, 2026, 15:30 - 17:00

Unlike RF/microwave amplifiers, phase noise of optical amplifiers is little studied. The literature reports on RIN or on optically carried microwaves, or is unsatisfactory for different reasons. The measurement of laser noise with/without amplifier is a common misconception.
We introduce a novel measurement method, topologically similar to the self-heterodyne but governed by different principles. Our scheme is a MZ interferometer with the amplifier under test (DUT) in one arm and an AOM in the other arm to shift the optical frequency. The beat between the two optical beams results in a RF signal v_b at the photodetector output, whose phase noise is equal to the DUT phase noise Sphi(f).
The scheme differs from the literature in that it does a true differential measurement, comparing the instantaneous input-output phase of the DUT to the 190 MHz RF oscillator. This is made possible by modern digital phase noise analyzers, which work with arbitrary input phase relationships, and accept multiple-cycle phase shift during the measurement.
We show the phase noise of an optical amplifier (Thorlabs BOA1550S) at different values of pump current and of input power, below saturation.
The white noise is consistent with the shot-noise model down to -126 dBrad2/Hz. The 1/f noise is <-32 dBrad2/Hz at 1 Hz (upper bound), equivalent to a fractional frequency stability ADEV of 5.2E-17/tau.

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Low noise distribution, transfer and measurement system for optical ultra stable signal.

Mr. Pierre Roset[1,2], Dr Gillot Jonathan[1,3], Dr Millo Jacques[1,3]
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We are developing, at FEMTO-ST, a system for low noise distribution, transfer and measurement of optical ultra stable signal. This system has a comparable architecture to the Time Processor. An optical local oscillator at 1542.14 is beat against the different optical references. One of this beatnote is used to phase lock the local oscilator, the others are counter thanks to a synchronous multi-channel phase-meter. Linear combinations retrieve the virtual beat-note frequencies between any of two references. This configurationis optimal for the three-cornered hat method which can be extended to include more references.
A optical frequency comb can be added to the system, with its repetition rate lock to the local oscillator, we can exted the system to RF, micro-wave, or other optical frequencies.
We also inclued phase-noise-compensated optical
fiber link to disseminate ultra stable signal through out the laboratory.
The objective of this project is to achieve a noise as low as 10-17 at 1 s without limiting any measurements. Details of the setup and the best performance results obtained will be presented at the conference.

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MIRIDIAN1 - an Integrated Optical Clock Based on C2H2

Dr. Andrew Attar[1], Dr. Henry Timmers[1], Bennett Sodergren[1], Dr. Asbjørn Jørgensen[2], Dr. Jürgen Appel[2], Dr. Jan Hald[2], Dr. Kurt Vogel[1], Dr. Kevin Knabe[1]
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Vescent Technologies, in collaboration with the Danish National Metrology Institute's (DFM), presents an overview of the MIRIDIAN$_1$ - an environmentally insensitive, low cost chassis-integrated optical molecular clock prototype for both government and commercial advanced timekeeping applications. System capabilities, initial instability performance, target performance, and ruggedization efforts of key photonic subsystems will be discussed.

Previous demonstrations of an optical clock based on acetylene (C_2H_2) molecules using commercial-off-the-shelf hardware, including robust optical frequency comb technology and optical frequency references based on narrow linewidth lasers stabilized to acetylene ro-vibrational overtone transitions, have been reported on in a prior EFTF meeting . Combining two critical subsystems, DFM's Stabilaser acetylene optical frequency reference and Vescent's RUBRIComb fiber-based optical frequency comb, allows users to assemble their own custom optical atomic clock that can be extended throughout the optical and down into the microwave. Vescent has set up a long-term measurement campaign where two acetylene optical clocks compare their 100 MHz outputs with a Rb-disciplined GPS unit to characterize the performance of these breadboard systems. At the time of submission, these systems have been operating phase-slip free for over 75 days without temperature control, vibration control, or user intervention and exhibits a long term noise floor below 3×10^(-13) (Fig. 1). Based on this performance, Vescent and DFM have begun integrating the breadboard system into a single turn-key solution, the MIRIDIAN$_1$. Prototype performance and environmental sensitivity will be discussed.

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Development of a compact fiber-based metrological system for frequency stability transfer over a wide spectral range using Bragg grating cavities

Mr. Yacine Chelouah[1], Mr. Mamadou Faye[1], Mr. Laurent Lablonde[2], Mr. Frédéric Du-Burck[1], Mr Vincent Roncin[1]
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We present a compact device for frequency stability transfer over the spectral band from 1.5 µm to 1.0 µm, based on two interleaved Bragg grating Fabry-Perot cavities, each resonating at one of two wavelengths.

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Trapping Laser System for Deployed Strontium Clock

Ms. Luz Martinez[1], Dr. Parth Patel[1], Mr. Dan Sheredy[1], Dr. Alex Chuang[1], Mr. Sean McCully[1], Dr. Martin Boyd[1]
[1]Vector Atomic

Poster session 1, April 21, 2026, 15:30 - 17:00

We present the development of a Strontium trapping laser system, containing wavelengths 461nm, 679nm, 707nm and 813nm, in a 3U chassis as part of a portable Sr lattice clock. The trapping laser system will work alongside a Sr chamber, enabling trapping of ultracold Sr atoms. Both have been configured to reduce the number of opto-mechanical components for a more compact system. We will highlight results from our laser testing and their integration with the Sr chamber.

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Implementation and Uncertainty in Real-Time Tri-Band GNSS Time Transfer

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GNSS common-view is used as a real-time or near real-time time transfer method. Expanding from the typically used L1 or L1/L2 signal bands to include L5 allows a reduction in the dominant noise sources to improve uncertainty. The additional signals per satellite allow reduced ionospheric delay estimation noise, reduced multi-path interference effects, and improved signal degradation resistance. In this paper, tri-band time transfer performance is compared against dual-frequency and the implementation difficulties in hardware and data processing for tri-band systems is discussed. The real-time tri-band common-view system is measured against alternative time transfer links where available and using remote clock stability for short term analysis. These improvements made to common-view techniques allow for simplified systems in applications where high accuracy and real-time time transfer is required but the accuracy of Precise Point Positioning (PPP) or similar techniques is not required nor their complexity justified.

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Microfabricated vapor cells with tunable buffer gas mix-tures using laser-actuated break-seal reservoirs

Gabriel Faure[1], Dr Clément Carlé[1], Andrei Mursa[1], Dr Shervin Keshavarzi[1], Dr Quentin Tanguy[1], Dr. Emmanuel Klinger[1], Dr Vincent Maurice[2], Dr. Rodolphe Boudot[1], Dr Nicolas Passilly[1]
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We report on the development and characterization of Cs vapor microfabricated cells filled with tunable buffer gas mixtures using laser-actuated break seal reservoirs.

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Stabilization of a semiconductor frequency comb in the 10E-15 range by optical injection and active phase correction.

Mr. Mamadou Faye[1]
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We stabilize the optical injection of a semiconductor frequency comb (Quantum-dash Fabry-Perot laser), integrated into a thermally regulated butterfly package and powered by a low-noise current source, by controlling the phase shift between the injection signal and the injected mode. This technique allows us to guarantee more robust injection and to study the long-term effect of the optical injection of the comb.

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Temperature-insensitive Two-way Phase Stabilized Optical Frequency Transfer

Miss Linlin Li[1], Mr. Ziang Qiu[2], Mr. Zijie Zhou[2], Mr. Hanzhao Zhong[2], Dr. Zhangjian Qin[1]
[1]Chengdu University Of Technology, [2]Shanghai Jiao Tong University

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Two-way optical frequency (TW-OFT) technology serves as a critical foundation for establishing long-distance optical clock networks, and has been widely applied in time-frequency metrology, gravitational wave detection, and navigation systems. Typical TW-OFT systems using asymmetric fiber interferometers which inevitably include out-of-loop (OOL) paths, in which non-reciprocal phase noise induced by the temperature fluctuations can severely degrade the long-term instability. Moreover, conventional TW-OFT systems rely on passive phase noise compensation method, meaning that the optical references transmitted in both directions still retain the link-introduced phase noise and cannot be used directly. Here we introduce a temperature-insensitive TW-OFT interferometer employing active compensation approach which can achieve phase-stabilized transfer for both two-way and one-way optical frequency signals. Experimental results demonstrate that the proposed interferometer effectively suppresses the annoying OOL noise and completely gets rid of the complex temperature control system. Compared to the conventional fiber interferometers, it can improve the long-term instability by one order of magnitude. Furthermore, for the 100 km fiber transmission, the instability for both two-way and one-way transfer reaches the 10-19 level, meeting the application requirements of the high-precision optical clocks to date.

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Calibration of time distribution fiber links containing regenerators

Dr. Lukasz Sliwczynski[1], dr. Przemyslaw Krehlik[1]
[1]Agh University Of Krakow

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Calibration of a fiber optic link containing optical-to-electrical-to-optical regenerators is discussed. Experimental verification of the procedure is provided showing the agreement between calibration and measured values at the distance of 500 km at the level of 15 ps.

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Distribution of accurate time and frequency using multi-core fibers

Dr. Lukasz Sliwczynski[1], dr. Przemyslaw Krehlik[1]
[1]Agh University Of Krakow

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Fiber optic time and frequency distribution system is considered using a multi-core fiber. Experimental verification over the distances of 20 km and 40 km confirms the assumptions about good noise compensation between the separate cores of the multi-core fibers, resulting in distribution inaccuracy at the level of a few times 10 to -17 at one day averaging and uncertainty at the level of a few ps.

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Ring laser gyroscopes in geodesy

Prof. Simon Stellmer[1], Jannik Zenner[1], Thomas Gereons[1], Prof. Heiner Igel[2], Prof. Ulrich Schreiber[3]
[1]University of Bonn, [2]LMU Munich, [3]TU Munich

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The precise determination of Earth orientation parameters is at the heart of space geodetic techniques and forms the basis for navigation both in Earth and in space. Over the past years, large-scale ring lasers have emerged as a new approach to complement space geodetic technique with continuous, local observations. From a technological point of view, ring lasers share concepts with both optical clocks and gravitational wave detectors and reach a fractional uncertainty in the interferometer readout below the 10^-20 level. We will present the current state of the field and detail technological advances.

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MODO: a Multi-GNSS and ADS-B Disciplined Oscillator with Integrity-Monitoring and Kalman Steering for Resilient Time and Frequency

Mr. Federico Vittorio Lupo[1], Dr. Ibrahim Osmani[1], Ing Simone Tozzi[1], Ing. Andrea Gramazio[1]
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Poster session 2, April 23, 2026, 15:30 - 17:00

This work presents MODO (Multichannel Optical/OCXO Disciplined Oscillator), a multi-source timing architecture conceived by the authors and co-funded by the European Space Agency under NAVISP Element 2. The system is currently being tested to demonstrate resilient time and frequency delivery with an end-to-end stability of 100 ns or better. MODO adopts a two-layer architecture: the first one aims at integrity-monitoring, the second one at steering the oscillator.
The first layer performs integrity-monitoring on up to four independent multi-GNSS receivers and on one ADS-B/Mode-S timing channel. ADS-B/Mode-S are standardized 1090 MHz aircraft broadcasts, periodically transmitted; when their time of emission is reconstructed on the ground, they can be converted into time-of-arrival (TOA) observables. For GNSS, integrity includes coherence checks among receivers and against the internal timescale, plus constellation- and receiver-level quality indicators. For the ADS-B/Mode-S channel, integrity is also performed on ΔTOE values derived from TOA measurements taken both at a master station at INRiM, directly tied to UTC(IT), and at the remote slave; TOA samples sent to a central server are used to reconstruct the emission time and derive the ΔTOE, i.e. the offset between the slave oscillator and the UTC(IT)-referenced master. GNSS or ADS-B channels whose filtered metrics exceed predefined thresholds are excluded before steering.
The second layer disciplines a high-stability local oscillator by means of a five-channel Kalman filter, with a multi-channel PI controller as operational option. The Kalman filter fuses up to four PPS offsets from integrity-validated GNSS receivers and ADS-B–derived steering already referred to UTC(IT), so that the remote slave can still be steered under local GNSS jamming or blockage. Initial tests with co-located MODO devices showed about 0.5 ns standard deviation on single ΔTOE/ΔTOA measurements, confirming that the ADS-B "standard service" is suitable as an in-dependent, UTC(IT)-traceable steering channel. A "premium service" based on full MLAT of ADS-B/Mode-S signals (solving aircraft position and emission time t) is foreseen to further improve accuracy and robustness. A multi-site campaign planned for Q1 2026, with INRiM (TO) as central node, will complete the validation using ADEV/TDEV/MTIE metrics, within the EFTF track on timekeeping and GNSS applications.

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Towards active superradiance clock with cold strontium atoms

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Poster session 2, April 23, 2026, 15:30 - 17:00

We present a progress towards an active optical clock with cold strontium atoms. The vacuum system is made of non magnetic materials like titanium, copper, glass and aluminum ensuring low magnetic susceptibility. Water cooled vacuum magnetic coils are specially designed in order to have excellent optical access with precise magnetic filed control up to 100 G. The coils are designed to be installed near the center of the main vacuum chamber, inside high finesse optical resonator for superradiance, in the way not to introduce any vibration the cavity. Additionally, we present a current control driver, that allows to stabilize current up to 150 A and to switch current direction in ms time scale. The whole system is designed for excellent control over the environment in order to utilize both 88 and 87 isotope of strontium atoms. We present the first tests of the system with cold strontium atoms.

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Rb microcells production for chipscale optical clocks

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Poster session 1, April 21, 2026, 15:30 - 17:00

We report on strategies for reliable series production of high-quality, evacuated microcells filled with rubidium atoms. These cells are critical for next-generation miniaturized quantum sensors and chip-scale clocks. The fabrication method uses anodic bonding and a two-cavity design, where microchannels separate the alkali dispenser from the sensing volume to prevent contamination of the sensing volume. We also present spectroscopic characterization using the Rb narrow-linewidth two-photon transition at 778.1 nm, and a new semi-automatic, wafer-level setup to rapidly screen the produced cells.

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Temperature dependency of birefringent effects in crystalline mirror coatings

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Poster session 2, April 23, 2026, 15:30 - 17:00

Crystalline AlGaAs/GaAs mirror coatings emerged as promising alternative to conventional dielectric mirror coatings for high-finesse optical resonators. However, in addition to their favorable optical properties, crystalline coatings exhibit intrinsic birefringence that fluctuates spontaneously and can be influenced by optical illumination.

We present measurements of the temperature-dependent frequency splitting of two polarization eigenmodes ("birefringent line splitting") in AlGaAs/GaAs crystalline mirror coatings from room temperature to 5 K. The measurements are conducted in a closed-cycle, low-vibration cryostat using a dual-frequency modulation technique to simultaneously lock on the average frequency of the two eigenmodes and track the birefringent line splitting.

Upon cooling from room temperature to 5 K the line splitting increases by about 5%. Furthermore, across the studied temperature range the response of the line splitting to sudden changes in intracavity power varies strongly in amplitude and transient duration.
We additionally extended our studies to nitrogen-dilute AlGaAsN/GaAs mirror coatings.

Our results provide new insights into the temperature dependency of birefringent effects in crystalline coatings and may contribute to improved models of birefringent noise sources, which in turn could lead to improved coatings for the next-generation ultra-stable optical resonators.

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Ultrahigh-stability Microwave Generated via Optical Frequency Division of an Ultrastable Laser

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Poster session 1, April 21, 2026, 15:30 - 17:00

Ultrahigh frequency-stability microwave signal sources are of great significance in a wide range of scientific and engineering fields. They find broad applications in areas such as high-performance antennas and radar systems, ultrafast electron sources [1], photonic analog-to-digital converters [2], and coherent communication technologies.
Driven by continuous advancements in microwave photonics technologies over the past decade, ultrastable continuous-wave laser-based systems have enabled the generation of ultrahigh frequency-stability microwave signals [3]. These systems are based on the optical frequency division of the stability of ultrastable continuous-wave lasers via an optical frequency comb [4].
In this paper, we report the generation of ultrahigh frequency-stability microwave signal sources based on the optical frequency division system with the fiber loop optical-microwave phase detector (FLOM-PD) technique [5]. We synthesize a 12-GHz microwave signal exhibiting a frequency stability of 4.3E-15/s via a ultrastable continuous-wave laser with the frequency stability of 2.0E-15/s.

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Testing Prototype Cavity with Minimized Temperature Coefficient of Resonance Frequency for Rb Fountain Clock

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Poster session 1, April 21, 2026, 15:30 - 17:00

The resonance frequency of the microwave cavity used in fountain clocks is highly sensitive to temperature. For a copper cavity, the temperature coefficient of the resonance frequency is approximately -100 kHz/°C. Therefore, to minimize frequency drift caused by cavity pulling and other effects, the allowable temperature variation in the environment where the atomic clock is installed must be kept very small. This requirement makes operating an atomic clock more complicated. To reduce the temperature coefficient of the resonance frequency, the use of dissimilar metals has been explored. In this study, a configuration was tested in which the cylinder is made of copper and the end-caps are made of aluminum. When the end-cap length is set to around 81 mm in a cylindrical cavity with an inner diameter of 77 mm, the temperature coefficient can be reduced to one-tenth or less of that of a uni-metal copper cavity. Using an FEM solver, the temperature coefficient for the actual resonator structure was calculated, and a prototype cavity was fabricated to compare the measured temperature coefficient with the predicted value. The temperature coefficients of the two uni-metal resonators were measured to be −145.2 kHz/°C for aluminum and −104.5 kHz/°C for copper, respectively. For the dissimilar-metal resonator composed of aluminum end-caps and a copper cylinder, the temperature coefficient was measured to be 11 kHz/°C. Based on these experimental results, the thermal expansion coefficients of the base materials were corrected, and the main dimensions of the resonator were re-optimized to finalize the design. At this conference, we present the design, simulation results, experimental procedures, and performance evaluation of the prototype cavity.

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Compact, digital controlled optical atomic clock

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Poster session 1, April 21, 2026, 15:30 - 17:00

We will present a compact rubidium two-photon optical clock which is compatible with a 4U chassis, and its SWaP is 60L, 50kg, 50W. Frequency stability is 1.2E-12 @ 1s.

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HYSTERETIC RESERVOIR COMPUTING WITH MEMS OSCILLATOR EXHIBITING PINCHED-HYSTERESIS

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Poster competition, April 21, 2026, 15:30 - 17:00

We report the first complex hysteretic reservoir computing (CHRC) based on a parametrically modulated, thus dynamically coupled Micro-Electro-Mechanical Systems (MEMS) oscillator, which exhibits the hallmark characteristic of memristors, i.e. pinched hysteresis. We evaluated the performance of the proposed reservoir computing system incorporating the MEMS resonator with pinched hysteresis behavior on the Nonlinear AutoRegressive Moving Average of order one (NARMA-1) task and preliminary results show that the CHRC system outperforms previous Duffing-nonlinearity-based systems in terms of accuracy, i.e., a mean normalized mean square error (NMSE) of 0.032 compared to previously reported 0.051. This result suggests that this approach has potential for future developments in in-sensor computation, where MEMS sensors can possess edge computation capabilities.

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A High-Precision and Automated Testbed for Fiber-Optic Time Transfer Equipment Calibration

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Poster session 1, April 21, 2026, 15:30 - 17:00

High-precision fiber-optic time transfer technology is fundamental to establishing the next-generation national time-frequency infrastructure. [1-6] However, the automated testing and comprehensive performance calibration of key fiber-optic time transfer equipment in China's major national scientific infrastructure projects—specifically the high-precision ground-based time service system—still lack a dedicated integrated test platform. [7-9] To address this chal-lenge, this paper presents the design and implementation of a test and calibration system for fi-ber-optic time transfer equipment and associated regeneration devices. The system enables au-tomated testing of multiple key components through deep integration of signal generation, pre-cision measurement, and control logic. Furthermore, the developed supporting hardware incor-porates integrated optical switches and noise generation modules, providing remote simulation capabilities for both link failures and programmable noise impairments. Combined with host computer software, the system automates the complete workflow from data acquisition and analysis to report generation. Experimental results demonstrate that the system achieves a time difference measurement stability less than 3 ps/s, a measurement uncertainty below 20 ps, and a phase resolution less than 1 ps. As a high-precision, integrated, and portable test platform, it significantly enhances testing efficiency for various fiber-optic time transfer and regeneration devices. This system provides crucial technical support for equipment testing and calibration within the high-precision ground-based time service system, demonstrating substantial engi-neering application value.

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Scaling high-accuracy Coulomb crystal clock operation to tens of ions

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Poster session 1, April 21, 2026, 15:30 - 17:00

Multi-ion clocks can provide both high accuracy and stability, as well as the possibility to combine favorable features of multiple atomic species. In our implementation with linear Coulomb crystals consisting of In+ (clock) and Yb+ (cooling) ions [1], we have scaled clock operation to 20-ion chains, while maintaining systematic uncertainties in the low 1e-18 range. We observe a scaling of the quantum projection noise limited instability of $1/\sqrt{N}$ with clock ion number N, reaching $\sigma(t) < 6$ e-16 / $\sqrt{t}$ for N = 8.

We present an analysis of the scaling behavior of various effects related to Coulomb crystal control and technical overhead under realistic operating conditions, which allows us to infer the potential and challenges for further increasing the ion number.

In addition, we experimentally investigate cooling of Coulomb crystals using the 1S0 - 3P1 transition in the In+ clock ions close to their ground state, with expected benefits to both stability and accuracy. Direct cooling of the clock ions will reduce the need for sympathetic cooling ions and thus allow an increased fraction of clock ions for a given crystal size. Temperatures near the ground state yield a time dilation shift below 2e-19, as opposed to > 1e-18 with Yb+ sympathetic Doppler cooling. With the achieved reproducibility and instability, this difference can be resolved spectroscopically within a few days.

Overall, we present a near-term path to a Coulomb crystal clock whose systematic and statistical uncertainties will allow for frequency ratio measurements with 1e-19 level uncertainties.

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Replicated Clock on an Unmanned Aerial Vehicle with Picosecond-level Precision in Three-dimensional Motion

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Poster session 1, April 21, 2026, 15:30 - 17:00

Unmanned aerial vehicles (UAVs) have been widely applied in various fields such as agriculture, transportation, and disaster monitoring due to their high mobility and flexible deployment capabilities. However, in high-precision missions such as communication, remote sensing, formation flight, and cooperative positioning, UAVs have stringent requirements for time and frequency precision. High-precision frequency standards on UAVs can not only provide frequency references for onboard equipment, but also contribute to inter-UAV clock synchronization, thereby better serving the aforementioned applications.

For high-precision missions, the frequency standards on UAVs need to be as stable as possible, while also considering the system complexity and payload capacity. To meet these requirements, we propose a frequency standard replication technology that uses a transponder and an active carrier-phase compensation method. By equipping UAVs with transponders featuring a simple radio frequency structure, picosecond-level precision frequency standards can be achieved onboard. Previously, we conducted a frequency synchronization experiment lasting 8,250 s on a hovering UAV. The results showed that the standard deviation was 7.65 ps, and the frequency stability reached 2.68e-12@1 s . To verify the performance of this method on the UAV in three-dimensional motion, we conducted another experiment in this study to measure the frequency synchronization precision of the replicated clock under the UAV's three-dimensional motion. The experiment was conducted under actual flight conditions, lasting approximately 60 s, with the UAV's trajectory covering approximately 1.09 m, 1.92 m, and 1.90 m in the x, y, and z directions respectively. The results showed that the standard deviation of the phase differences between the replicated clock on the UAV and the reference clock on the ground was 3.07 ps. The frequency stability, characterized by the Allan deviation, reached 4.74e-12@1 s. The performance did not deteriorate significantly. The replicated clock achieved picosecond-level precision, which was superior to the commonly used oscillators on UAVs.

The realization of replicated clocks on UAVs with picosecond-level precision under dynamic conditions will improve the precision of various UAV-related applications, such as positioning, navigation, monitoring, and mapping. This advancement is also expected to create new application opportunities for UAVs, such as serving as experimental platforms equipped with high-precision frequency standards for scientific research.

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A Road-Mobile GNSS-Disciplined Oscillator for Nanosecond-Level Synchronization in Vehicular Applications

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Poster session 2, April 23, 2026, 15:30 - 17:00

Precise synchronization is essential in various technical disciplines, being especially challenging in mobile scenarios. Unfortunately, state-of-the-art global navigation satellite system (GNSS) disciplined oscillators (GNSSDOs) are designed and optimized for stationary operation, i.e., fixed position and no dynamic accelerations.
In this paper, we present a novel solution that is designed for mobile use from the ground up. The centerpiece is a precise oven-controlled crystal oscillator (OCXO) that is optimized for low sensitivity to dynamic accelerations. A state-of-the-art GNSS timing module is used to discipline it, featuring multi-constellation and multi-band capabilities to suppress ionospheric effects. Furthermore, differential GNSS with timing correction information is employed to augment synchronization accuracy.
We evaluate the system by comparing it with state-of-the-art test equipment for laboratory use, the FS740 by Stanford Research Systems, outfitted with the optional rubidium timebase. For this purpose, we conducted a real-world test drive through diverse environments: between high-rise buildings, over rural roads, and highways, as well as moving in tight circles as an acceleration stress test. After compensating for the stationary offset, one FS740 device deviated from the reference by up to 2315 ns, while the other was never more than 280 ns out of sync. This significant variation in performance indicates severe instability in this environment. With the new GNSSDOs, in contrast, the deviation never exceeded 22.6 ns. It is evident that the devices designed for laboratory use perform inadequately in mobile operation and that our novel solution enables a significant leap in accuracy.

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On the correction of differential light shifts in an optical dipole trap

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Optical dipole traps (ODTs) have applications for precision measurements with ultracold at-oms, yet differential light shifts (DLS) limit their application in clock metrology. While optical lattices and magic wavelengths have been successfully explored to minimize these shifts in tai-lored setups, this increases the complexity of systems and thus reduces the versatility of ODTs in frequency reference measurements. This is especially true for setups where a magic wave-length is not available, e.g. when Alkali atoms as Cs and Rb are used.
We propose an approach to cancel DLS by utilizing time-averaged potentials to create intensi-ty-varying arrays of atomic clouds. We present a general cancellation scheme and show prelim-inary experimental results with ultracold Rb atoms forming a microwave clock. This work lays the foundation for potential improvements in trapped-atom clocks and explores the possibility of application into other areas of precision sensing.

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Time-keeping for the aircraft with celestial objects

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In deep-space where GPS/BEIDOU signals are unavailable, spacecraft must rely on onboard atomic clocks for precise timekeeping. However, atomic clocks that cannot be calibrated will gradually accumulate timing errors, and these deviations grow exponentially over time. This underscores the necessity of autonomous calibration technologies or multi-clock redundancy systems for long-duration missions beyond Earth's orbit.

Leveraging millisecond pulsars—neutron stars emitting highly stable X-ray pulses with timing stability rivaling atomic clocks—this technology enables autonomous time-keeping. In addition, atomic clock timekeeping innovations now enable drift correction via pulsar timing residuals, eliminating reliance on GPS/BDS signals or long-time drift of the atomic.

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Demonstration of Broadband VLBI Receiver Calibration with Atomic Clock-Referenced Optical Frequency Combs

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This work presents a practical solution for phase calibration in multi-frequency VLBI systems by implementing atomic-clock-referenced optical frequency combs at the Korean VLBI Network. An optical pulse train, locked to a local hydrogen maser, is delivered via a stabilized fiber link from the observatory building to the antenna, where direct photodetection generates a broadband RF comb signal up to 50 GHz for receiver calibration. This approach overcomes the limitations of conventional electronics-based PCAL methods, providing broadband calibration tones that are fully compatible with multi-frequency VLBI systems.

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Yb+ isotopes spectroscopy and tests of fundamental physics

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Poster session 1, April 21, 2026, 15:30 - 17:00

Trapped ytterbium ions can be used for tests of fundamental physics. We measured isotope shifts of the E2 (411 nm) and E3 (467 nm) optical transitions across five stable spinless ytterbium isotopes. This enables searches for a possible new boson mediating an additional interaction between neutrons and electrons. Using King plot analysis, we test for deviations from linearity and combine our data with atomic-structure calculations to study the quartic change in the nuclear charge radius along the isotopic chain, in order to have information on nuclear deformation. We placed an upper bound on the coupling strength of such a hypothetical new boson.

We also report the first observation of the forbidden E3 transition in $^{173}Yb^{+}$. Its deformed nucleus produces a strong hyperfine-induced electric dipole contribution, enhancing the forbidden E3 transition. Using King plot estimates, hyperfine corrections, rapid adiabatic passage, and polarization aligned to E1 selection rules, we successfully excited the most quenched hyperfine state. The measured lifetime of the $F_e = 4$ state is 12 times shorter than the unquenched value, showing that this decay is dominated by the hyperfine-induced channel. The measured rates differ from theory, and possible explanations are discussed.

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Research on BeiDou Satellite Time Synchronization Based on Ka-Band Inter-Satellite Links

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Due to the lack of global ground monitoring stations, BeiDou relies on Ka-band inter-satellite links (ISLs) installed on every BeiDou-3 satellite to maintain constellation-wide time and orbit determination. By two-way Ka ranging between satellites and only a few domestic TT&C sites, the system achieves autonomous operation. We process 30 days of ISL data: after modelling and correcting ionospheric, relativistic, antenna phase-centre and other biases, the two-way measurements are converted into relative clock offsets with respect to reference satellite C25. A quadratic fit removes the onboard clock trend, leaving residuals that contain only bidirectional measurement noise plus unmodelled systematic errors; their RMS therefore quantifies ISL two-way time-transfer precision. For C28 and C29 the RMS values are 0.39 ns and 0.42 ns, respectively, demonstrating that BeiDou's Ka ISLs already deliver sub-nanosecond constellation synchronization without global ground coverage.

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Laser frequency reference using a microfabricated vapor cell with formable film getter for vacuum maintenance

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Poster session 1, April 21, 2026, 15:30 - 17:00

We present a compact laser system based on a micro-fabricated Rubidium (Rb) vapor cell in-corporating formable Ti-film getters for in-situ vacuum maintenance. The vapor cell enables Doppler-free saturated absorption spectroscopy (SAS) with two lithographically patterned chambers. The porous Ti-film can be patterned into arbitrary geometries within the chambers, enabling flexible integration with microfabricated cell architectures. We verify the sustained vacuum conditions by measuring the Doppler-free SAS linewidths and comparing them with those obtained from cells using conventional non-evaporable getters. In addition, we measure the stability of the resulting laser frequency lock.

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Transportable laser-cooled trapped-ion optical atomic clocks for space and terrestrial applications

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Optical atomic clocks demonstrate lower systematic frequency uncertainty and a better stability than the top performing microwave atomic clocks. The current state-of-the-art optical clocks have a large footprint in a laboratory environment and require specialist skills to maintain continuous operation. As such, transportable optical atomic clocks (spaceborne and terrestrial) could offer transformative capabilities for future science, navigation, and Earth observation programmes.

A transportable laser-cooled strontium-ion optical atomic clock is being developed at NPL with the goal of supporting the redefinition of the second, and ultimately towards space deployment. The 88Sr+ system has demonstrated excellent performance in the laboratory, and crucially has reduced size, mass, laser power and complexity compared to many alternatives. The increasing availability of commercial DBR/ DFB laser technology to manipulate the 88Sr+ ion allow optical systems to be constructed mainly from commercial off-the-shelf fibre-coupled components.

Our approach has been focussed on the development of a multi-wavelength dual-axis cubic-cavity-stabilised clock control unit suitable for space or ground deployment, in addition to more compact and robust ion trap physics packages. An updated design for a single ion trap has been developed at NPL and it is now undergoing testing. Finite element simulations have been conducted to model the response of the trap to vibration, shock and thermal conditions typically encountered during launch and space deployment. Additionally, an electrostatic model has been developed to investigate the relationship between the ion trap geometrical tolerances and the trapping efficiency.

Combining these technologies provides a pathway towards high-performance and robust transportable optical clocks.

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SENSEI project: sensing on the EU metrology fiber network

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Poster session 1, April 21, 2026, 15:30 - 17:00

Optical fibers are the most pervasive infrastructure that covers our planet. When equipped with optical technologies that measure deformations, they can be turned into a global sensing system, useful for seismic hazard monitoring, cable safety and optical data transmission quality supervision. To support this vision on a large scale, several challenges must be accounted for, both in technological development and design of an architecture for data collection and interpretation.

The SENSEI project, funded within the Horizon Europe program for 2025-2027, addresses these challenges with a consortium of 15 members, that include Earth scientists, networking experts and operators, photonic developers and members of the optical frequency metrology community. The project develops sensing techniques that measure and localize mechanical deformations with sub-km accuracy with no disruption to data traffic and tests them extensively in various environmental scenarios. The role of the frequency metrology community is central to this task, contributing key technologies such as ultra-low noise lasers and coherent laser interferometry techniques. SENSEI will also employ the European clock-comparison fiber network as a testbed (Fig. 1), showcasing its use as a multidisciplinary research infrastructure. In parallel, we are designing protocols that enable efficient collection and combination of heterogeneous datasets from different sensing nodes, to fully integrate fiber sensing into the telecom network architecture and turn collected data into exploitable information. At the conference, we will present the project, results from the first year and way forward.

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Miniaturized Optical Frequency Standard

Dr. Qiaohui Yang[1]
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Poster session 2, April 23, 2026, 15:30 - 17:00

Frequency is one of the physical quantities with the highest measurement precision, and many physical measurements can be converted into frequency measurements. Optical frequency standards provide the highest accuracy and stability among time-frequency devices. However, high-performance optical frequency standards are usually large and complex, making it difficult for them to operate outside laboratory environments. Therefore, reducing the system size while meeting application requirements is of great importance.
In this work, we miniaturize multiple components, including the laser, atomic vapor cell, and photodetector, and construct a compact optical frequency standard. Phase modulation spectroscopy is used to obtain a high signal-to-noise-ratio optical spectrum. The optical module of the compact system measures 50 mm × 53 mm × 28 mm, with a total volume of only 74.2 mL. Despite the significant reduction in size, the system achieves a beat-note frequency stability of 8×10^{-13} at 1 s and a self-evaluated stability of 6.5×10^{-14} at 1 s.
This miniaturized optical frequency standard provides a pathway toward extending optical frequency standard technology to applications such as navigation and communication.

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A New White Rabbit Switch with Clock Holdover Capabilities

Mr. Daniel Chung[1], Mr. Ricardo Píriz[1], Mr. Aravind Subbiah[1], Mr. Alon Sechan[1], Mr. Binish Mathew[1], Mr. Satyam Ashitosh[1], Mr. Vikas Singh[1], Mr. Nick Amey[2], Mr. David Cocks[2], Ms. Amanda Díez[3], Mr. Quentin Genoud[3], Mr. Harvey Macdonald Leicester[3], Mr. Maciej Lipinski[3], Mr. Javier Serrano[3], Mr. Adam Wujek[3]
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Poster session 2, April 23, 2026, 15:30 - 17:00

White Rabbit (WR) is a GNSS-independent, open-hardware technology for time and frequency distribution over optical fibre. Born at CERN (the European Organisation for Nuclear Research) as a result of a collaborative effort to synchronise devices in particle physics experiments, WR is gradually being adopted for other applications. These applications include comparison of distant atomic clocks, synchronisation of antenna arrays in distributed radio-telescopes, and accurate timestamping of transactions in the stock exchange, to mention just a few. WR provides sub-nanosecond accuracy and picosecond precision, making it ideal for synchronising large distributed systems.

The latest produced version of the WR switch is v3, available off-the-shelf from different vendors worldwide. The design and prototyping of its successor, WR switch v4, is currently being led by CERN. One of the main features of this new version is the inclusion of an expansion board to easily customise the product for particular applications. As the first example, we are developing a v4 switch together with an expansion board to provide clock holdover capabilities (shown in Fig. 1).

Holdover is the capacity of a clock to maintain accurate time when its synchronisation source is disrupted or temporarily unavailable. The expansion board integrates a Rubidium Chip-Scale Atomic Clock (CSAC) utilising quantum Coherent Population Trap (CPT) to achieve a highly stable frequency and improved holdover capabilities.

The new WR switch with the holdover expansion board covers the widely adopted requirement (e.g. telecom) not to exceed 1.5 microseconds after 24 hours. Additionally, some applications in telecom and finance require maintaining ns-level synchronisation accuracy for 5 to 10 minutes during network reconfiguration, which is also supported. Fig. 2 shows the long-term and short-term holdover capabilities of the switch.

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Frequency transfer with medium frequency R-Mode

Dr. Lars Grundhöfer[1], Dr. Stefan Gewies[1], Carsten Rieck[2]
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Poster session 2, April 23, 2026, 15:30 - 17:00

Synchronization of many distributed technical applications is over-dependent on GNSS. Jam-ming of GNSS spectrum is already a common problem and coherent spoofing of signals is a real-istic thread for critical infrastructure using GNSS for its time and frequency references.
This study demonstrates the feasibility of one-way frequency transfer using medium-frequency (MF) R-Mode, a technique previously deployed for positioning in the maritime domain but now adapted for high-stability timing.
The R-Mode system requires precise frequency transfer to keep the station synchronized without dependencies from other systems. One opportunity to do this is by imple-menting R-Mode self-synchronization capabilities using the MF R-Mode ranging signals. To val-idate this approach, we extended the DLR MF R-Mode receiver to generate a 10 MHz reference by correcting a local oscillator using R-Mode phase measurements. Laboratory tests over coaxial cable (with synchronized transmitter and receiver clocks) isolated hardware-induced errors, con-firming feasibility for GNSS-denied environments while demonstrating resilience against path noise and phase instability.
Field validation occurred during the Jammertest 2025 in Norway, where a temporary R-Mode station was established. We successfully measured the drift of a rubidium atomic clock, which provided a 10 MHz signal, using R-Mode phase data and validated its drift against a local refer-ence during extended operation. Long-term analysis of an existing MF R-Mode transmitter ena-bles possible mitigation techniques for the transmitter imperfections of the MF R-Mode system.
Compared to DCF77 and GNSS (vulnerable to jamming), MF R-Mode delivers an alternative to frequencies transfer in contested environments while maintaining robustness against interference. Its maritime applicability is confirmed through field tests, where signal propagation over water paths exhibited minimal noise, positioning R-Mode as a viable complementary solution for mari-time navigation, critical infrastructure timing, and GNSS backup in high-threat zones.
In the paper we characterizes the performance of MF R-Mode in typical environments and com-pare to GNSS and DCF-77 in different configurations.
Future work will optimize R-Mode parameters, enhance transmitter stability, and develop real-time phase-jump compensation algorithms. This research establishes MF R-Mode as a practical, deployable alternative for time and frequency transfer where GNSS is compromised - without requiring two-way communication or satellite infrastructure. MF R-Mode in a network configura-tion will also offer dependable timing as part of the output of an R-Mode navigation receiver, most suitable for maritime applications.

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A 3D diamond ion trap with integrated optics for frequency metrology

Dr. Anand Prakash[1], Mr Erik Jansson[2], Mr Hemanth Kalathur[2], Dr Elena Jordan[2], Prof Dr Tanja Mehlstäubler[1,2]
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Poster session 1, April 21, 2026, 15:30 - 17:00

We will present a segmented linear Paul trap with integrated optics and fibres, featuring four spectroscopy segments. All segments of this trap can be probed simultaneously. These features make the trap a versatile setup for addressing the scaling of the number of ions in a trap segment, thereby reducing quantum projection noise, as well as being suitable for implementing advanced clock protocols, such as cascaded and zero dead-time clocks.

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A Compact Strontium Atomic Beam Source Enabled by a Two-Dimensional Grating MOT

Dr. Hyun Gyung Lee[1], Dr. Jae Hoon Lee[1]
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Plenary session 1, April 21, 2026, 08:30 - 10:15

We present a compact two-dimensional grating magneto-optical trap (2D gMOT) for strontium that generates a slow atomic beam using a single input laser. The configuration of the atomic dispenser and grating chips enables efficient atom capture while preserving the long-term performance of the grating surfaces. The 2D gMOT produces an atomic flux of 2×10^8 atoms/s with a mean velocity of 6.4 m/s. This grating-chip-based systems for laser cooling and trapping supports further miniaturization and offers a path toward portable ultra cold atom systems.

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Mitigating environmental influences on an ultra-stable industrial clock laser system

Dr. Maria Romodina[1], Dr. Florian Schäfer[1]
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Poster session 2, April 23, 2026, 15:30 - 17:00

Ultra-stable optical local oscillators are essential for atomic experiments and applications such as optical clocks, quantum simulators and quantum computers. External cavity diode lasers locked to high-finesse optical cavities are commonly used as such oscillators. However, enviromental noise limits the frequency and phase stability of such systems. Here, we present our strategies for mitigating the impact of various types of important environmental noise sources, enabling us to achieve a fractional frequency instability of less than 2×10^{-15} at an averaging time of 1 s for the TOPTICA Clock Laser System.
Sources of noise affecting the stability of cavity-referenced lasers include air pressure fluctua-tions, temperature variations, seismic and acoustic noise, optical power fluctuations, and fiber noise. To minimise the impact of pressure fluctuations, we maintain a stable air pressure of less than 5×10^{-8} mbar in the vacuum chamber using an active ion pump. This also helps to isolate the cavity from environmental temperature fluctuations. The cavity is further encased within several thermal shields. One inner thermal shield and the vacuum chamber itself are actively temperature-controlled using two finely tuned feedback loops, ensuring temperature stabilization at the 0.1 mK level. The three orders of magnitude suppression of temperature fluctuations has been proven experimentally. Peak-to-peak oscillations of 2.0 °C in the external temperature lead to temperature changes of 0.001 °C at the cavity shield. Such slow variations are typical of day-night temperature cycles and are very challenging to suppress using passive temperature isolation.
Beyond pressure and temperature effects, the poster presentation will also provide a detailed dis-cussion of our approaches to minimize the impact of the other major external noise sources that are of mechanical and optical nature.
The presented noise mitigation strategies result in a highly stable system, with relative instabilities in the 10^{-15} regime for a large range of averaging times. Combined with its compact, rugged design, this makes the system a stable, reliable and easily deployable platform for advanced sensing, metrology and quantum applications.

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Group Delay Measurement for Enhancing Spectral Hole Center Pointing and Reducing Laser Locking Frequency Drifts

Mr. Axel Robbes[1]
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Poster competition, April 21, 2026, 15:30 - 17:00

We report group delay measurements via phase modulation for laser frequency stabilisation on spectral holes in Eu:YSO crystals.

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Sub-Nanosecond Wireless Time Synchronization via OFDM Pilot-Based Fractional Timing Estimation

Mr. Shirong Wei[1], Mr. Liangcheng Deng[1], Mr. Dong Zhang[1], Dr. Fu Zheng[1], Dr. Chuang Shi[1]
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Poster competition, April 21, 2026, 15:30 - 17:00

This paper addresses the fundamental limitation of timestamp resolution imposed by signal bandwidth in wireless Precision Time Protocol (PTP), which hinders the achievement of sub-nanosecond synchronization required for next-generation wireless systems. We introduce a novel, two-stage method that moves beyond conventional packet-based approaches by leveraging the phase offset information inherent in OFDM pilot symbols. Our solution first establishes a coarse synchronization via standard PTP, then refines it by converting the hardware-level channel estimate of the pilot phase into a high-resolution fractional timestamp. Theoretically, we derive the Cramer-Rao Lower Bound for this fractional estimate and establish its relationship with the number of OFDM points. Simulations show that across a wide range of SNR conditions, the proposed method significantly reduces clock offset standard deviation compared to conventional wireless PTP, achieving about 0.9 ns versus 11 ns with the conventional approach. A real-time prototype implemented on a ZCU102 FPGA platform with an AD9361 RF transceiver consistently attained sub-nanosecond accuracy in indoor line-of-sight environments, confirming its practical potential for next-generation high-precision wireless systems. Moreover, compared to conventional TOA methods, the technique offers not only higher precision but also greater robustness in multipath scenarios.

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π-Phase-Difference Ramsey Cavity Design for Rubidium Beam Clocks

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Poster session 2, April 23, 2026, 15:30 - 17:00

The rubidium atomic beam provides a choice for constructing optical beam clock without the use of laser. How to improve the signal-to-noise ratio of such an clock has always been an im-portant challenge . Previous studies on cesium beam clocks show that Ramsey cavities with a π-phase difference could effectively suppress noise and reduce frequency shifts. In this work, we present a design of π-phase-difference Ramsey cavity for compact rubidium atomic beam clocks.

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Coordination of Clock Steering and Timescale Generation over a Swarm of Satellites

Mr. Leo Sol[1], Mr David Valat[1], Ms Alexane Ramaye[1], Mr Jérôme Delporte[1]
[1]Cnes

Poster session 1, April 21, 2026, 15:30 - 17:00

Satellite swarms are one of the trends in the space sector, due to their new-space aspect (same platform for each satellite) and their ability to produce distributed measurements, which opens up the possibility of new missions combining autonomy, reconfiguration, and robustness. However, the challenges of network architecture, communication, and synchronization are critical and require upstream studies. The CNES Time-Frequency team has worked for several years on synchronization techniques for swarm on-board clocks, especially on the Inter-Satellite Links that provides clock bias.
The synchronization of the swarm can be performed by steering each satellites's clock on a master clock, belonging to a master satellite. While conceptually simple, such approach has a major weakness in terms of robustness. A more robust approach would consist in using every clock available to define a robust time reference, tolerant to few clock failures. This paper presents the implementation of a real-time timescale using up to 30 clocks in a laboratory test bench designed to reproduce the time-frequency behavior of a satellite swarm : The currently available inter-satellite links performs one-by-one measurements (time-division multiple access, TDMA), which implies a specific sequencing of measurements that will be described in the paper. The results of the timescale implementation, considering these constraints, are compared to the ideal case where all measurements are available at all times.
To be properly synchronized, the onboard clocks of the swarm should be physically steered on this computed time reference, while the clocks must otherwise remain free-running in order to contribute to timescale calculation. We propose a new solution to this apparent dilemma, based on a numerical method of free-running clocks reconstruction using measurements of the steered clocks. The results of the experimental implementation of this solution are presented in the second part of the paper.
Finally, we expose and discuss the overall performances of clock synchronization on the reconstruction-produced timescale introduced in the second part.

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Compact fiber-based dual-cavity system for multiple laser stabilization

Dr. Tommaso Petrucciani[1], Irene Goti[1], Matteo Barbiero[1], Carmelo Grova[2], Michele Montanari[3], Olmo Artesani[2], Giada Meogrossi[2], Federico Lavorenti[4], Alessandra Tortora[4], Mario Siciliani de Cumis[5], Giancarlo Natale Varacalli[6], Danilo Vicari[6], Marco Pizzocaro[1], Filippo Levi[1], Davide Calonico[1]
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Poster session 2, April 23, 2026, 15:30 - 17:00

In this work we present a compact dual-cavity architecture designed to provide full laser stabilization for a transportable 171Yb optical lattice clock. The primary contribution of this work is the generation of the Pound-Drever-Hall (PDH) error signals of all lasers required for atomic cooling and trapping through a fully fiber-based setup with dimensions of a single 19” rack unit. In-fiber dichroic mirrors and optical circulators have been employed to minimize the free-space optics: only three fiber outputs, each followed by a lens and a mirror, are needed to stabilize five lasers to a multi-color transfer cavity (MCC) by Stable Laser Systems. The MCC drift is corrected through a slow feedback loop acting on the cavity piezo, using the clock laser stabilized to a high-finesse ORC-Cubic cavity (CC) by Menlo Systems as a reference. All the PDH error signals have been optimized, and the full system is currently under characterization, including measurement of the clock laser’s fractional instability via beat-note comparison with a second laboratory-based ultra stable laser. Robustness tests of the setup involve displacing the dual cavity system outside the laboratory frame in a realistic transport simulation, to verify its capability to resume operation without performance degradation.

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Sr Optical Lattice Clocks and Their Comparisons at NIM

Dr. Yige Lin[1], Mr. Tangyin Liao[2], Mr. Hao Liu[3], Dr. Fei Meng[1], Dr. Qiang Wang[1], Dr. Tao Yang[1], Dr. Haochen Tian[1], Dr. Bingkun Lu[1], Dr. Ye Li[1], Dr. Baike Lin[1], Dr. Zhanjun Fang[1]
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Poster session 2, April 23, 2026, 15:30 - 17:00

Two Sr optical lattice clocks are being developed and operated at the National Institute of Metrology (NIM). They are located on different campuses of NIM which are more than 40 km apart. A 58-km noise canceled fiber link is built to transfer both optical and microwave frequencies to connect the two campuses. Two optical frequency combs with adapted single-branch configuration is adopted to make the frequency comparisons. The measured fractional frequency difference between these two Sr clocks is 1.9 (3.2)E-17, which is within their claimed uncertainties.

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Space qualification of a rubidium two-photon frequency reference

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Poster competition, April 21, 2026, 15:30 - 17:00

We report on the space qualification of an optical rubidium two-photon frequency reference. This spectroscopy module is a key component for the payload CRONOS that will demonstrate the operation of an optical clock in low Earth orbit in a small satellite mission.
We use the |5S1/2, F=2> to |5D5/2, F=4> transition in 87Rb at 778.1 nm. The transition is probed by frequency modulation spectroscopy with less than 20 mW of optical power in a 1 mm beam diameter. The light double-passes a 1 cm glass-blown vapor cell, heated to ~100 °C, with crossed polarizations. Fluorescence at 420 nm is collected by a compact lens system and spec-trally filtered before impinging onto a SiPM detector. For application on the satellite mission the module has to withstand vibration, shock, thermal cycling and radiation.
We recently finished the assembly integration of a qualification module of the spectroscopy unit , shown in Fig. 1. The module is designed for in-vacuum operation and optimized for low-outgassing while providing maximum thermal isolation from the rest of the payload. It occupies a volume of ~ 0.55 L, has a mass of 700 g and consumes less than 2 W of electrical power in steady-state operation. Preliminary tests indicate a fractional frequency instability of the refer-ence below 1.5×10-13/√τ at 1 s integration time.
We present design details related to the environmental constraints and report on the mechanical and thermal qualification of the spectroscopy module. This includes 1000 g shock, vibration and thermal-vacuum cycling between below -20 °C and above +60 °C in non-operational mode. We will further investigate the frequency instability of the module by operation of multiple spec-troscopy modules in a temperature-controlled vacuum chamber and report on its temperature sensitivity.
This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Eco-nomic Affairs and Energy (BMWE) due to an enactment of the German Bundestag under grant numbers 50WM2164 and 50WM2564.

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Ultra-low phase noise from X- to the terahertz-band via comb-based frequency division and synthesis

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Poster session 1, April 21, 2026, 15:30 - 17:00

Frequency-comb-based generation of radiofrequency, microwave and mm-wave signals with rec-ord-low phase noise becomes increasingly important for a variety of applications, e.g. in navigation, radar and communications . Here, using an offset-free comb, we report ultra-low noise 9.6 GHz microwaves reaching -165 dBc/Hz using optical frequency division (OFD) and show tuna-ble sub-THz frequency synthesis (0.1-0.5 THz) for characterization of RF components .

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Compact dispersion-managed fiber laser based on a polarization-maintaining hybrid module

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Poster competition, April 21, 2026, 15:30 - 17:00

Ultrashort-pulse fiber lasers with a high repetition rate and a sufficiently broad spectrum have played a vital role in many applications, such as frequency metrology, precision measurement, and optical frequency combs. The fiber laser based on nonlinear amplifying loop mirror (NALM) mode locking offers long-term stable operation. However, its repetition rate is fundamentally limited by the cavity length, resulting in a low repetition rate that severely restricts its applicability. In this study, we demonstrate a compact dispersion-managed fiber laser based on a polarization-maintaining (PM) hybrid module. The compact spatial-optics module design significantly reduces the laser cavity length, and the volume of the fiber laser is much smaller than that of most previously reported systems. Finally, by simultaneously controlling the cavity dispersion and length, we demonstrate a fiber laser operating at a high repetition rate of 210 MHz with a broad spectrum. The 3-dB spectral bandwidth is 78 nm, and the compressed pulse duration is 100 fs. Through the carrier-envelope-offset frequency detection module, the carrier-envelope-offset frequency (fceo) with a signal-to-noise ratio (SNR) of approximately 40 dB is obtained. The fiber laser features a simple and environmentally stable structure, providing a solid foundation for the development of practical optical frequency combs.

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Unified Error Analysis for Microwave Satellite–Ground Time Transfer: Kinematic, Relativistic Periodic, Atmospheric, and Hardware Delay Effects

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Poster session 1, April 21, 2026, 15:30 - 17:00

High-precision satellite-ground time transfer is a fundamental capability for establishing unified time reference systems and supporting satellite navigation and deep-space exploration. Its achievable accuracy is largely constrained by the proper modeling and mitigation of multiple systematic errors along the propagation path. Considering low-, medium-, and high-Earth-orbit scenarios, this study develops a unified error analysis framework for satellite-ground time transfer and rigorously derives the formation mechanisms and propagation characteristics of four major error sources: geometric (kinematic) delay, relativistic effects, atmospheric delays, and hardware-induced delays. First, the geometric relationship between the satellite and ground station is used to quantify the kinematic delay biases caused by geometric range and orbit errors, highlighting the amplification of orbit errors in the time-transfer observable and their strong sensitivity in both one-way and two-way links. Second, the relativistic analysis focuses exclusively on periodic effects associated with orbital motion, demonstrating how variations in satellite velocity and gravitational potential introduce periodic timing modulations, and evaluating their typical amplitudes for different orbital regimes. Third, ionospheric and tropospheric models are employed to characterize residual atmospheric delays under varying elevation angles and propagation geometries, showing that such residuals remain a dominant limitation for high-precision time transfer. Hardware delays are treated as fixed but uncompensated biases, potentially exhibiting slow variations driven by temperature or equipment states; differences in hardware delay magnitude between code and carrier measurements are emphasized due to their impact on different link configurations. The results indicate that geometric delay, atmospheric residuals, and hardware delays constitute the primary error sources in current space-to-ground time transfer, while the periodic relativistic effects introduce noticeable modulations at the orbital timescale. The analysis supports improved error modeling, observation strategies, and performance optimization for next-generation time-transfer systems, with applicability to BDS, GPS, GALILEO, and future Earth–Moon and deep-space timing missions.

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Characterization and Performance of an Optical Frequency Comb for Space

Ms. Hannah Tomio[1], Ms. Charlotte Zehnder[2], Dr. Kohei Yamamoto[3], Dr. Guangning Yang[3], Dr. Holly Leopardi[3], Dr. Andrew Attar[4], Dr. Henry Timmers[4], Dr. Kevin Knabe[4], Dr. Kurt Vogel[4]
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Poster session 1, April 21, 2026, 15:30 - 17:00

Optical frequency combs have increasingly become ubiquitous tools in the field of precision metrology, due to their broad utility in optical and electronic frequency synthesis and measurement. As on Earth, there are numerous uses for frequency combs in space missions, in scientific applications as well as for communications and positioning, navigation, and timing (PNT). These diverse comb applications include their use as calibration tools for high resolution spectrograph instruments, in free space laser terminals for high precision ranging and time transfer, and for transfer-ring phase stability to and from the optical and RF/microwave domains for highly stable frequency references from optical oscillators, such as optical atomic clocks and cavity-stabilized lasers. These uses can advance the search of Earth-like exoplanets and enable new space-based tests of fundamental physics.

While the utility of frequency combs for space-based applications has been recognized, their full capabilities have yet to be demonstrated through sustained operation in orbit. Previous demonstrations include the launch of a femtosecond mode-locked laser to low Earth orbit (LEO) and single and dual frequency combs systems on sounding rocket flights. More recently, a frequency comb system has been installed as part of an optical atomic clock payload on the Chinese Space Station, and an extensive comb experiment is proposed in the form of the COMPASSO mission, intended to demonstrate optical clocks and time transfer from the International Space Station.

In work complementary to these efforts, we present the characterization and performance of a spaceflight-compatible erbium-doped fiber frequency comb from Vescent Technologies. This ruggedized, modular comb system is radiation-hardened-by-design and consumes 5 W of power. It has been subject to environmental testing (thermal vacuum, vibration and shock, radiation) consistent with operation in LEO. We describe the characterization of the residual phase noise and frequency stability of this comb system as compared to similar, laboratory-grade devices, including via the three-cornered hat measurement technique. While limited by the noise floor of our measurement instrument at certain timescales, the residual comb noise was found to be ~5.5 x 10^(-17) at 1000 s (in terms of fractional frequency stability).

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Key performance metrics of an integrated two-photon Rb optical atomic clock prototype

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Poster session 2, April 23, 2026, 15:30 - 17:00

We present a 19” rack-mounted optical clock based on the single-color two-photon excitation of ^{87}Rb, optimized for high stability and low SWaP. Built around robust C-band photonics and mature fiber technology, this platform supports autonomous operation and integration into terrestrial and space-based timing infrastructures. Developed by CSEM and Rolex Quantum, the system has transitioned from laboratory validation to operational UTC contribution via METAS. The clock architecture uses a continuous-wave laser at 1556.2 nm, phase-modulated, amplified, and frequency-doubled to drive the $5S_1/_2 \rightarrow 5D_5/_2$ two-photon transition in a hot vapor cell. Resulting fluorescence at 420 nm is detected and demodulated to generate an error signal for laser stabilization. A self-referenced optical frequency comb phase-locked to the laser provides RF outputs for end users.
The integrated prototype presented here comprises modular bays for the comb, atomic reference, and control electronics, engineered for hands-off operation and long-term stability. Its performances match laboratory-grade ones, with a tunable short-term stability between 2×10^{-13} and 6×10^{-14} at 1 s and a slow drift of 6×10^{-15}/day, confirming that integration does not compromise stability. In particular, the system features a fast warm-up time below 1 h and a typical measured retrace value of 9×10^{-15} measured after an 8 h complete shutdown, which enable short holdover recovery times and minimized synchronization transients. The clock frequency sensitivity to external thermal fluctuations was measured below 2×10^{-15}/K, limited by the measurement time, both for the control electronics and atomic reference units, in accordance with theoretical estimates and design requirements. In addition, absolute frequency measurements of the clock transition frequency are well aligned with literature.

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Search for Dark Matter by Spectroscopy of Acetylene using Ultra-Stable Optical Fibre Links

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Poster session 2, April 23, 2026, 15:30 - 17:00

Precision laser spectroscopy of an acetylene transition at 1.5 µm is addressed in view of direct detection of wavelike ultralight dark matter (UDM) formed with 0-spin, sub-eV-energy particles. The principle of the experiment is to search for fast oscillations in the laser spectroscopy signal, that depends on the sensitivity coefficient of the acetylene transition to the variations of the fundamental constants, the experimental frequency transfer functions, and the UDM coupling coefficients to the Standard Model (SM) fields. The experiment exploits directly the REFIMEVE ultrastable optical reference at 1542 nm, transferred from the Paris Observatory through 2×340 km phase-stabilized optical fiber links to the PhLAM laboratory, where interrogates off-resonantly linear absorption of the acetylene transition with 10^(-12)-level precision. The Fourier spectrum of the photodetection signal is exploited to estimate bounds of the couplings of the Galactic UDM to the SM.

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Systematic uncertainties in a commercial Sr+ optical clock

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Poster session 2, April 23, 2026, 15:30 - 17:00

A systematic shift evaluation for Stable Laser System's strontium ion clock will be presented. Operation at the strontium ion magic frequency, near Doppler-limited ion temperatures, low heating rates at 2 mK/s as well as very low thermal gradients due to the trap being constructed on a diamond wafer enable an accurate clock. Preliminary measurements show the blackbody radiation shift uncertainty likely to be in the low 1E-18 range.

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Optimizing UTC(k) Time Generation Using Bang-Bang and LQG Algorithms

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Poster session 2, April 23, 2026, 15:30 - 17:00

The precision of frequency steering algorithms directly affects the performance of UTC(k), in-cluding its phase noise level, long-term frequency stability, and accuracy relative to interna-tional UTC. Commonly used frequency steering algorithms primarily employ bang-bang and LQG algorithms. Bang-bang control is an on-off strategy that uses extreme control inputs to quickly return a system to its target state, leading to rapid responses but potentially causing oscillations in UTC(k) timekeeping. In contrast, LQG (Linear Quadratic Gaussian) control is an optimal strategy based on state estimation, which is effective in noisy environments but requires high model accuracy and is sensitive to noise and uncertainties.

This article introduces a high-precision time generation method for UTC(k) that optimizes two frequency control strategies using a weighted switching function. The weighted switching func-tion dynamically evaluates the system state based on the control error and system stability to select the most appropriate frequency steering strategy. Advanced steering algorithms, particularly in addressing nonlinear factors such as atomic clock frequency drift, can significantly enhance the reliability of UTC(k) and maintain time deviations within sub-nanosecond levels.

We developed an experimental system that employs an optimal steering algorithm to evaluate its impact on UTC(k) time generation. The experimental results, shown in Figure 1, indicate that the time differences between the steering time UTC(Test) and the national standard time UTC(NTSC) are maintained within ±0.5 ns over a two-month period. Additionally, Figure 2 demonstrates a stability of 7.5E-15@1day. These results highlight the effectiveness of the high-precision UTC(k) time generation method, which not only reduces error fluctuations but also improves stability by adjusting the frequency steering strategy.

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Kalman Filtering Atomic Time Algorithm Improved Based on Sage-Husa and Variational Bayesian Filtering

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Poster session 2, April 23, 2026, 15:30 - 17:00

To generate accurate, stable, and reliable time scales, the atomic clock ensemble at the Time-keeping Laboratory requires effective atomic time algorithms and efficient steering methods for the production and transfer of time scales. Currently, the internationally common approach-es are the weighted-average-based ALGOS or AT1 time scale methods, while some laboratories employ the Kalman filter time scale method. Given the limitations of the ALGOS method in terms of short-term stability performance in composite atomic time and the suitability of the AT1 method only for small-scale clock ensembles, we adopted an improved Kalman filter time scale method for the computation and steering of composite atomic time. By integrating the Sage–Husa filter and the Variational Bayesian filtering algorithm to estimate the measure-ment noise covariance matrix (R) and the process noise covariance matrix (Q), we could miti-gate the divergence issue of the Kalman filter time scale method and achieve a composite atomic time with real-time capability and favorable short-term stability. This method offers a new approach for composite atomic time generation in some regional time-keeping laboratories.

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High-Precision Optical Fiber Time Transfer: A Current-Temperature Dual-Loop Wavelength Locking Scheme for DFB Lasers

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Poster session 2, April 23, 2026, 15:30 - 17:00

High-precision, picosecond-level time transfer over optical fiber is imperative for advancing fundamental science, high-technology engineering, and national defense[Zuo. F. “Fiber-optic joint time and frequency transmission with enhanced time precision”. Opt. Lett. vol.47, p.1005-1008, 2022.][V. Kudriashov. “On Lab Test of Coherence in Event Horizon Imager”. 2021 EFTF/IFCS, pp. 1-6.2021.]. However, its performance is fundamentally limited by chromatic dispersion[Hong. Huibo. “Quantum Two-Way Time Transfer Over a 103 km Urban Fiber”. JLT. vol. 42, no. 5, p. 1479-1486, 2024.]. In Wavelength Division Multiplexing (WDM)-based two-way fiber time transfer , mitigating this impairment hinges on enforcing stringent wavelength symmetry between counter-propagating signals[P. Krehlik. “Electrical Regeneration for Long-Haul Fiber-Optic Time and Frequency Distribution Systems”. IEEE-UFFC, vol. 68, no. 3, p. 899-906, 2021].
Here, we introduce a high-precision time transfer method that overcomes this limitation through a dual-loop current-temperature wavelength locking scheme for Distributed Feedback (DFB) lasers. Operating within a same-wavelength, time-division multiplexing TWFTT architecture, our system leverages optical heterodyne detection to derive a real-time error signal corresponding to the wavelength mismatch. This signal drives a dedicated feedback loop that simultaneously tunes the laser's injection current and temperature, achieving robust, wide-range wavelength locking. This active stabilization minimizes dispersion-induced asymmetry, leading to a substantial enhancement in both time transfer uncertainty and long-term stability.
The system's performance was experimentally verified on laboratory fiber links up to 200 km, consistently achieving a time transfer uncertainty below 10 ps. In a field trial over a 203 km link (103 km terrestrial + 100 km spooled fiber) between the National Time Service Center (NTSC) campuses, we demonstrated a time transfer uncertainty of 5.8 ps. The corresponding time stability was 4.2 ps at 1 s, improving to 1.61 ps at 80,000 s.
These results validate our method as a robust and practical solution for ultra-high-precision time transfer over long-haul distances, establishing a viable pathway toward next-generation timing networks for demanding scientific and engineering applications.

Quantum-Referenced 795 nm DBR Laser using Hybrid Atomic Self-Injection and MTS Locking

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Distributed Bragg Reflector (DBR) lasers are desirable for quantum sensing and atomic physics due to their compactness and potential for integration. However, their widespread application in precision measurement is hindered by their MHz-scale free-running linewidths, limited frequency stability, and inability to automatically align with atomic resonances. While conventional self-injection locking can narrow linewidth, the absence of a direct quantum reference leads to long-term frequency drift and unconfined mode-hopping, necessitating frequent recalibration.

To address these challenges, we present and demonstrate a two-stage turnkey 795 nm DBR laser locked to the ^{85}Rb D_1 line via both atomic self-injection locking and MTS locking. Stage 1 utilizes frequency-selective optical feedback by integrating a Faraday anomalous dispersion optical filter (FADOF) into the external cavity to automatically confine the laser frequency to the ^{85}Rb D_1 line, providing robust, maintenance-free operation. This feedback significantly narrows the Lorentzian linewidth from 81.09 kHz (free-running) to 2.32 kHz. The mechanism is theoretically analyzed using an adapted Lang-Kobayashi model for side-mode locking.

Stage 2 further locks the laser frequency to the ^{85}Rb $5^2S_{1/2}$ F=3 → $5^2P_{1/2}$ F′=2 transition, combining an active feedback loop with modulation transfer spectroscopy (MTS). The complete dual-stage system (see Fig. 1) achieves a fractional frequency stability of $4.63 \times 10^{-13}/\sqrt{\tau}$.

The demonstrated turnkey operation and excellent frequency stability make this system an ideal low-noise laser source for demanding applications, including atomic clocks, atomic gravimeters, and laser cooling. Furthermore, we propose a flexible architecture that enables switching between the optically locked narrow-linewidth mode and a free-running DBR mode with wide and continuous tuning range. This allows a single compact source to serve for both high-precision and broad spectroscopic scanning purposes.

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Ultra-Precision Offset Frequency Locking of lasers Using Mixer-Based Frequency Subtraction and a Balanced Filter Technique

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We present a novel ultra-precision offset frequency locking technique of two lasers using mixer-based frequency subtraction and a balanced filter method. The system utilizes a two-channel signal generator to feed local oscillator frequencies into mixers, where the beat frequencies are subtracted. The resulting differential signal passes through low-pass filters to achieve precise frequency offset stabilization. Unlike traditional phase-locking methods, this approach does not require phase synchronization, making it more robust for applications where phase stability is not critical. Experimental results show long-term stability with Allan deviations as low as 5 × 10^-15 at 1-second integration times, offering a flexible solution for high-precision laser systems.

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Zero-dead-time operation of 113Cd+ microwave clock

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Poster session 2, April 23, 2026, 15:30 - 17:00

The Dick effect limits the short-term frequency stability of pulsed atomic clocks, and suppressing it is essential for further enhancing clock performance. The zero dead time (ZDT) technology em-ploys two or more atomic clock systems to alternately compare the frequencies of atoms with the local oscillator, thereby completely eliminating deadtime and enabling the clock's Allan devia-tion to evolve as τ^{-1}.
This work realizes a microwave ion clock based on ZDT, which effectively suppresses the Dick effect and improves the performance of the clock. Using two sympathetically cooled $^{113}Cd^{+}$ mi-crowave clocks as the foundation, we established a ZDT experimental system and successfully conducted the experiment on the ZDT-based clocks.
We constructed two identical vacuum ion trap systems and separately measured the Ramsey clock transition signals for Systems A and B. Additionally, we performed closed-loop locking experiments on both the single sympathetically cooled $^{113}Cd^{+}$ microwave clock and the ZDT-operated clocks, and characterized their respective frequency stabilities.

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Thermal Expansion of Cordierite-Based Optical Cavities

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Poster session 2, April 23, 2026, 15:30 - 17:00

Dimensionally stable Fabry-Perot resonators are essential for many high-precision instruments, from optical clocks to spectral calibrators required for exoplanet research. All applications require outstanding length stability of the resonators and thus extremely low coefficients of thermal expansion (CTE). In addition to a very small CTE with zero crossing at room temperature, cordierite ceramics shows a larger Young's modulus, a smaller length drift and a smaller mechanical loss factor then ULE glass. This makes cordierite ceramics an attractive spacer material. We have measured the effective CTE of a 100 mm long cordierite-based cavity with ULE mirrors and used finite element analysis to determine the impact of the CTE mismatch between ULE mirrors and cordierite spacers on the cavity's CTE. Using the known CTE of the mirrors, we were able to determine the true CTE of the cordierite spacer material. We found that the slope of the CTE is about ten times higher than that of ULE glass. We analyze the impact of this high value on cavities with fused silica mirrors and propose CTE-optimized cavity designs.

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European ultra-stable atomic clocks

Ground Active Hydrogen Maser: Status and progress report

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Poster session 1, April 21, 2026, 15:30 - 17:00

High-ends atomic clocks are critical to ensure the reliable and sustainable functioning of the ground-based infrastructure that supports European space activities, most visibly ESA’s deep space antennas as well as critical timing and navigation facilities, notably such as GALILEO reference. Yet, these systems rely heavily on non-European technology.
In order to secure an independent European supply chain, ESA and T4S/Safran Timing Technol-ogies have co-founded a development program of an ultra-stable atomic clock technology for the ground segment entirely developed, designed and built in Europe.
This paper proposes an overview of this program, the first results obtained, and next steps toward achieving fully state-of-the-art performances for a frequency reference designed for high-level operational sites.

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Research Progress of Optical Frequency Standards at Huazhong University of Science and Technology

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Due to their higher Q values, optical frequency standards are better than the best microwave frequency standards both in stability and accuracy, and have many important applications in precision measurement and metrology. The BIPM is in the process of redefining “second” based on optical frequency standards, and has setup a roadmap to achieve that. In this report, we will present the research progress on the development of quantum logic based Mg+-Al+ ion optical clock at Huazhong University of Science and Technology. By carefully investigated the influence of the applied bias magnetic field, a suitable value is selected to enable smaller quadratic Zeeman shift while has negligible impact on other frequency shift. The latest total systematic uncertainty of the optical clock has been improved from 1.6E-18 to 5.2E-19, and our ongoing works to satisfy the roadmap requirements would be discussed.

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A Survey of PNT Standards for GNSS Based Applications: Landscape, Gaps, and Implications

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Poster session 2, April 23, 2026, 15:30 - 17:00

Positioning, Navigation, and Timing (PNT) services underpin Global Navigation Satellite System (GNSS) based applications across telecommunications, finance, transportation, and cooperative intelligent transportation systems (C-ITS), where resilient synchronisation and accurate timing are critical performance enablers. This paper presents a comprehensive review of the current PNT standards landscape spanning SAE, BSI/ISO, and IEEE, together with the most relevant UK/EU policy context. The work examines mature and work-in-progress documents, including SAE J3269, IEEE 1588, BS EN 16803, SAE J2945/x, and ISO 34503 and evaluate their stated scope and applicability to GNSS-based synchronisation and hybrid PNT systems across three layers: user equipment, augmentation (e.g., RTK/PPP), and distribution.

Three cross-cutting observations emerge. First, the landscape emphasises user-equipment testing while giving limited, uneven treatment to system-of-systems interactions and end-to-end assurance. Second, validation emphases and performance metrics vary by sector (automotive, telecom, and safety-critical infrastructure), complicating the portability of test evidence and slowing harmonisation for GNSS applications. Third, policy and regulatory drivers in the UK/EU increasingly shape expectations around resilience, security, and interoperability, yet the linkage from those objectives to measurable conformance outcomes remains weak.

The findings point to literature-grounded gaps: fragmented validation with limited end-to-end treatment of dependencies between receivers, augmentation services, and distribution networks; incomplete resilience/assurance coverage and inconsistent terminology/ taxonomies. The paper provides an evidence-based map of what is covered versus what remains open, intended to support researchers, implementers, and standards participants working at the intersection of GNSS applications and PNT standardisation.

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SI-traceable molecular frequency measurements around 30 THz within sub-kHz uncertainty

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We report recent ultra-high-resolution spectroscopic studies of methanol and ethylene in the mid-infrared (MIR) region using frequency modulation cavity-enhanced saturated absorption spectroscopy. Record line center frequency uncertainties ranging from a few kilohertz down to several tens of hertz are achieved. In our setup, a 10 µm quantum cascade laser (QCL) is phase-locked to an SI-traceable 1.54 µm metrology-grade reference signal from the REFIMEVE network via a mode-locked optical frequency comb, thereby transferring the spectral purity and stability of the near-infrared reference source to the MIR region. This approach creates an SI-traceable and ultra-stable MIR source with a relative frequency uncertainty of 10^{-14} and a linewidth of ≃0.1 Hz at 1s. Current developments to enhance the spectrometer performance are also presented, in particular the use of a new generation of fast MIR detectors that can significantly improves spectral tunability.

The spectrometer was operated under two distinct regimes: (i) the optically thin regime for methanol transitions in the ν_8 vibrotational band, and (ii) the optically thick regime for ethylene transitions in the ν_7 fundamental band. In both cases, cavity transmittance noise originating from frequency-to-amplitude conversion and molecular spectral lineshape have been investigated in details. This has allowed us to reach uncertainties smaller by nearly three orders of magnitude compared to HITRAN database. Notably, a state-of-the-art statistical uncertainty of 57 Hz and a systematic uncertainty of 437 Hz were obtained for the (J',ka',kc' = 9,2,8) <- (J",ka",kc" = 9,3,6) ethylene transition, thanks to a reduced cavity transmittance noise under optically thick conditions. The present setup, with optimized experimental conditions, represents a powerful tool for high-resolution measurements aimed at improving and refining molecular databases, as well as testing fundamental physics. With the current accuracy, laboratory spectra can already be directly compared to high-resolution astronomical observations to search for possible variations in the electron-to-proton mass ratio me/mp over cosmological time scales. Looking forward, achieving relative frequency uncertainties at the 10^{-15} level would open the way to more stringent tests, such as the search for parity-violating energy differences between enantiomers of chiral molecules and variation of me/mp in the present epoch.

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Preliminary Characterization of a Thermo-Optically Tunable L-Band OEO based on a Silicon Nitride Ring Resonator

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Oscillator, Resonator, Tunability, Optoelectronics

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Interspecies clock comparisons and chronometric geodesy using a transportable optical lattice clock

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After laboratory optical clocks have reached fractional frequency uncertainties of few 10^(-18) and below, it is an ongoing task to miniaturize these complex devices and to make them transportable without compromising their performance. This effort is motivated in part by promising applications in geodesy. Together with accurate frequency transfer techniques, e.g. via interferometric fibre links (IFLs), these clocks can measure gravitational potential differences in the 0.1 m^2/s^2 regime. Thus, they could help to establish a unified height reference system. Additionally, transportable clocks are indispensable devices for inter-institute clock comparisons, when long-distance fibre links are not available.

Here, we present a high-accuracy measurement of the optical frequency ratio between a stationary {171}^Yb^{+} single-ion clock operating on the electric-octupole (E3) transition and the second-generation PTB transportable {87}^Sr lattice clock. We measure the local frequency ratio, ν(Yb^{+}/ν(Sr), with a fractional frequency uncertainty close to 5×10^{-18}, representing one of the most accurate interspecies clock comparisons to date. The transportable clock was also operated off-campus at the Max-Planck Institute of Quantum Optics (MPQ) in Garching, Germany, where its frequency was compared with the stationary clock via a ~940 km long IFL. This remote comparison enabled us to perform a direct measurement of the geopotential difference – i.e., chronometric levelling – between the two locations. The result agrees with the independent determination using the GNSS/geoid approach and represents a fivefold improvement in accuracy on our previous measurement , resolving a height difference with an uncertainty of ~5 cm.

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Preliminary assessment of the White Rabbit link between INRiM and EC-JRC

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This paper presents a preliminary performance assessment of the White Rabbit (WR) link between from INRIM (Turin, Italy) to the EC-JRC (Ispra, Italy) over a 300 km optical fiber link. The WR timing signal received at EC-JRC was assessed against a local pivot clock simultaneously compared to UTC(IT) using state-of-the-art satellite techniques.

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Almost unattended time scale based on a single commercial cold Rb atomic clock

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This paper presents the generation of a time scale based on a commercial cold Rb clock with minimal effort while fulfilling the requirements of a UTC(k) realization.

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Characterization of a doped-silicon surface-electrodes trap for optical frequency metrology

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It has been shown that the best optical atomic clocks outperform the best cesium clocks that currently define the second unit. For this reason, many laboratories around the world are aiming to make optical atomic clocks transportable, to be integrated into a wide range of applications. Our goal is to develop a compact single-ion clock based on the 171Yb+ ion using the quadrupole transition at 435.5 nm. Our targeted fractional frequency instability is on the order of 10-14 τ-1/2. The transportable aspect is in part determined by the type of trap used. We chose to use a surface-electrodes trap with gold-coated doped silicon electrodes, designed and fabricated in FEMTO-ST. We will present the full characterization of this trap including measurements of the trapping frequencies, excess micromotion compensation by synchronous detection of a parametrically excited motion, measurements of the saturation intensity of the cooling and repumping transitions, lifetime estimation of the ion and heating rate measurements based on the Doppler re-cooling method.

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Frequency Transfer Over 80km of Fiber Supporting the NIST-to-Mt. Bluesky Clock Comparison

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Through coordination with multiple fiber network owners near the Boulder, CO area, including the Adams 12 Five Star Schools, The Front Range GigaPoP, and The University of Colorado, an 81 km dark fiber path linking NIST Boulder Labs to an Adams 12 School District rooftop is established. The frequency of a 1550 nm CW laser, locked to an optical clock at NIST and transferred over this link, locks two frequency combs which in turn transfer the NIST clock signal over a free-space link between the rooftop and an observatory on the peak of Mt. Bluesky (~69 km of free-space and ~2700 m of elevation change) for comparison to a second clock located there. The fiber path passes under roads, through network closets and other noise-inducing infrastructure. Full doppler cancellation of this link supports a fractional frequency instability of 5e-18 at a 300 second averaging time in an initial test of the optical clock comparison.

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Er doped LiYF4 as a solid-state oscillator

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Rare earth ions embedded in solid matrices have been considered for new technological applications due to their features such as narrow absorption linewidths across a broad spectral range - from the UV to the NIR - and long coherent lifetimes of their excited states . These peculiarities arise from the fact that 4f intrashell transitions are basically insensitive to external perturbations. Overall, lanthanides hosted in crystals are an attractive platform for modern laser and telecommunication industry, quantum information storage, signal processing and communication . These characteristics are appealing also for the realization of optical solid-state secondary frequency references for space applications .
Among the fifteen rare earth elements, Er3+ ion stands out due to its narrow transition at the telecom wavelength (1550 nm) which allows seamless chip-scale integration with existing fiber-optic communication technologies, lasers, and photonic devices . On the other hand, lithium yttrium fluoride (LiYF4) single crystal has proven to be one of the most promising hosting candidates for the high-resolution study of the spectroscopic lines of Er3+.
We will present the spectroscopic characterization that we performed on a sample of 166Er3+:7LiYF4, with an Er concentration of 35 ppm. We achieved a ~20 MHz inhomogeneous linewidth for the transition from the ground state to the first excited state using 1530 nm laser radiation at 4 K and a small magnetic field. By locking the laser to this transition, we obtained an Allan deviation of 2×10^{-12} at 1 s, demonstrating a first step toward the prototyping of an optical solid-state secondary frequency reference for space applications.

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Operational Characterization of Laser Frequency Stability on a Wide Spectral Range

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We report the implementation of a Moku:Pro phasemeter in the LTE frequency metrology chain to characterize lasers with broader linewidths, as required in applications such as the LISA mission. Traditional frequency counters struggle to measure frequency noise of laser of linewidth in the 10 Hz–10 kHz range. The Moku:Pro, with its 1 MHz tracking oscillator and dead-time-free acquisition, enables continuous frequency noise measurements across a wide spectral range. Preliminary comparisons with K+K frequency counters on ultra-stable lasers at 1542 nm and 1062 nm show good agreement, confirming its metrological relevance. Further developments target full operational integration and characterization of lasers at 1560 nm and 1596 nm for space missions.

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Construction of an 171Yb Optical Lattice Clock for Geodetic Exploration

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In this paper, we present recent progress on the assembly of our 171 Yb transportable optical lattice clock ROYMAGE at LTE (Laboratoire Temps Espace). This instrument aims at controlling the clock frequency over 18 digits or better, in order to explore the coupling of atoms to the Earth gravitational potential. With the goal of performing measurements along the fiber link network REFIMEVE throughout France, remote comparisons to other European optical clocks will help further constraining geodetic models. We focus on the assembly of the science chamber and coils, as well as on our first 3D Magneto-Optical Trap. Furthermore, we describe our atomic loader RAZPOUTYNE, characterized by a unique design combining 2D MOT and Zeeman slower and present our first loading results.

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Software Defined Radio Devices for Optical Frequency Metrology

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Poster session 1, April 21, 2026, 15:30 - 17:00

We report on an SDR platform implementing three all-digital devices: 1) An rf phase-frequency meter allowing additional signal processing, e.g. for real-time transfer-beat generation, 2) a phase stabilizer for optical path length stabilization, and 3) a phase comparator with extremely large capture and holding range for robust laser phase locks. We have equipped the setups of an optical frequency comb and of the end-to-end phase stabilized distribution of ultra-stable reference light (Fig. 1) with these SDR-based devices, completely dispensing their analog electronics counterparts. We demonstrate the overall performance and show the benefits of monitoring the systems and their vitality parameters in a time-series database.

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Stability Analysis of TWSTFT and PPP Time Transfer Links Based on the Three-Cornered Hat Method

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Poster session 2, April 23, 2026, 15:30 - 17:00

The current international standard time, UTC, is generated by the BIPM through the synthesis of free atomic time scales produced by commercial atomic clocks from over 80 timing laboratories worldwide. This is further corrected by the frequency standards of primary/secondary frequency standards from some laboratories. The key to achieving this global coordination lies in high-precision time comparison links, which are the necessary technical means for connecting atomic clocks and primary/secondary frequency standards distributed across different locations. However, time comparison links must be calibrated before they can be formally used for UTC calculation. Due to the high costs and operational complexity involved, calibration activities are difficult to conduct frequently. And the stability of time comparison links can affect multiple key indicators in UTC generation, including the accuracy of the links themselves, the frequency of link calibration, and the uncertainty evaluation of calibration results. Therefore, ensuring stability of time comparison links is crucial for improving the accuracy and reliability of UTC.
Two-Way Satellite Time and Frequency Transfer (TWSTFT) and GPS Precise Point Position-ing (PPP) time transfer are currently the most precise long-distance time comparison methods used in UTC calculation, with over 90% of atomic clocks worldwide being compared through these two methods. Research indicates that when the atomic clocks at two locations are hydrogen masers or cesium clocks, the noise of the atomic clocks for averaging times less than one day is significantly smaller than the link noise. Therefore, the short-term stability of TWSTFT and PPP can be directly derived from the link results. However, for averaging times greater than one day, atomic clock noise dominates, making it difficult to reflect the true stability of the time comparison links from the clock difference comparison results. The Three-Cornered Hat (TCH) method is commonly used in the time and frequency field to evaluate the relative frequency stability of individual atomic clocks. This method can also be applied to time comparison systems. To obtain the long-term and short-term stability of TWSTFT and GPS PPP time comparison links, we use six months of data from SATRE TWSTFT, SDR TWSTFT, and GPS PPP time comparison links between NTSC and PTB. The results show that when the averaging time is less than 1 day, the time deviations of the GPS PPP and TWSTFT links are ranging from 80 ps to 300 ps. When the averaging time beyond 1 day but remains less than 10 days, the TDEV values of both TWSTFT and GPS PPP links, maintaining a stability level between 40 ps and 100 ps.

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A Transportable Yb-based Optical Lattice Clock for High-Accuracy Applications

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Poster session 2, April 23, 2026, 15:30 - 17:00

Transportable optical clocks based on neutral atoms and single ions have proved to be valuable tools for high-accuracy applications. Their exceptional stability and accuracy enable to test fundamental physics, to perform high-precision timekeeping and to conduct geodetic measurements at the cm-level. In fact, compared to GNSS-based techniques, transportable optical clocks allow for an alternative approach to topographic studies using chronometric leveling, by a direct measure of the earth gravitational field through clock frequency shift.
In this paper, we report the green-field development of a transportable optical lattice clock (OLC) based on neutral Ytterbium (^{171}Yb) atoms. The device is developed by Leonardo S.p.A., Kayser Italia S.R.L. and the Italian National Metrology Institute (INRIM), funded by ASI (Ital-ian Space Agency). The OLC targets a relative frequency stability of 10-15 at 1 s, an accuracy of 5*10-18 and an optimized SWaP (Size, Weight and Power) for transportation. The system is composed by three standard 19’’ racks, each with specific functional purposes, ready for field deployment. The architecture combines both commercial components and novel design solutions, integrated in a modular design to increase compactness and maintainability. At the core of the system, an Aluminum dodecagonal science cell enables in-vacuum spectroscopy of cold ^{171}Yb atoms loaded in a magic wavelength lattice. Sisyphus cooling is employed to enhance atomic control within the lattice, enabling operation at lower trap depths, which in turn reduces both density and lattice shifts. The Black-Body Radiation (BBR) shift is evaluated using a BBR model, whose uncertainty is limited by the thermal gradient in the spectroscopy chamber, which is kept within 10mK. To assess the thermal map, calibrated thermistors are embedded into the mechanical body of the science chamber. Additionally, a fast atomic shutter, operating at 3Hz, blocks the BBR from the Yb oven during clock spectroscopy. To run the OLC five laser sources are integrated on a single, compact, transportable rack, and are stabilized through two optical cavities with high-finesse and Pound-Drever-Hall (PDH) locking scheme. A custom made ArtiQ architecture manages clock operations and signal distribution in real-time within a single, integrated, compact platform.
The OLC will undergo tests at system-level both in controlled and representative environments. To this purpose, the Italian Quantum Backbone offers a unique asset, connecting INRIM facilities in Turin (IT-TO) with high-altitudes locations in the Alps, ASI geodesy center in Matera (IT-MT) and INAF radiotelescope in Medicina (IT-BO). The project positions itself within the few OLC developed to date. With its transportable design, this development aims to expand state-of-the-art OLC performances outside laboratories.

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Sub-kHz, RF-traceable Frequency Comb with Dual-Domain Stabilization and Automated Locking

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Poster session 2, April 23, 2026, 15:30 - 17:00

We present a dual-loop-stabilized DFG frequency comb providing simultaneous spectral purity and SI-traceable frequency accuracy. The scheme avoids the cost and complexity of high-finesse cavity-stabilized systems while delivering sub-kHz linewidths. A comb-comb comparison demonstrates an H-maser-like long-term stability limit. Fully automated locking and a unified GUI make the system a universal optical reference for quantum-optics experiments.

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Coupled Quartz Crystal Resonators with Active Thermal Stabilization for Achieving a Higher Frequency Stability

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Poster session 1, April 21, 2026, 15:30 - 17:00

Quartz resonators are widely used as timing devices due to their high precision and low power consumption. However, their frequency stability is strongly affected by temperature fluctuations. AT-cut quartz is highly temperature-sensitive, exhibiting a temperature coefficient of frequency of approximately 1 ppm/°C at 25 °C. Therefore, even a small variation in ambient temperature can cause significant frequency drift. To mitigate temperature effects, thermal isolation setups have been employed, achieving frequency stability in the range of ~5 ppm. While this reduces drift, it remains insufficient for open-environment operation, and commercial thermally stabilised systems are often expensive and bulky.
In this work, we present coupled crystal resonators fabricated on a single substrate with an integrated micro-heater and temperature sensor for active thermal control. This design reduced frequency drift from 7.5 ppm to 2 .3 ppm, achieving a ~70% improvement over operation with a conventional Peltier heater. The approach offers a compact, low-cost solution for high-stability timing applications under variable environmental conditions.

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Analysis of collision shift assessments in ion-based clocks

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Poster session 1, April 21, 2026, 15:30 - 17:00

We consider collision shifts in ion-based clocks using a simple hard-sphere model in conjunction with the long range attraction between an induced-dipole and the ion. We treat the problem both classically and quantum mechanically and generalize the interaction using a Lennard-Jones type potential, which give consistent quantitative agreement. Our results show the sensitivity of the collision shift to changes in the interaction potentials, which can be understood from the simple hard-sphere model and the WKB approximation. In addition we show that the shift can be bounded by the classical Langevin collision rate and factor that characterizes the decoupling of the ion from the clock laser. We show that the collision shift assessments given in the literature using calculated molecular potentials significantly over-estimate the collision shift.

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The improvement of the frequency stability of an atomic ce-sium fountain at HUST

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Poster session 1, April 21, 2026, 15:30 - 17:00

We have developed a cesium atomic fountain clock (HUST-CsF1) at Huazhong University of Science (HUST), which is used for realizing the time and frequency traceability of the National Precise Gravity Measurement Facility (PGMF). The stability of the HUST-CsF1 is optimized with the home made cryogenic sapphire oscillator (CSO) used as local oscillator. The HUST-CsF1 and the CSO are located in two different budlings, separated 1 km. The ultra stable performance of CSO was transferred to the lab of HUST-CsF1 via a commercial frequency transfer and the 9.192631770 GHz discrimination signal for HUST-CsF1 was generated by home-made Frequency Synthesizer based on the 100 MHz signal transferred from CSO lab. Besides the local oscillator, the molasses cooling of Cesium, detection system and the magnetic of the system were also optimized for the frequency stability and the stability of the HUST-CsF1 is improved from 2×10-13/√τ to 5×10-14/√τ. With the improvement of the frequency stability, the evaluation time for systematic uncertainties will be significantly reduced.

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Performance comparison of photonic microwave generated via optical frequency division and cryogenic sapphire oscillator at KRISS

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Poster session 1, April 21, 2026, 15:30 - 17:00

A high-finesse cavity-locked continuous wave laser serves as the local oscillator for optical clocks. Such a laser not only exhibits exceptional long-term frequency stability but also demon-strates excellent short-term stability and ultralow phase noise. When this laser is combined with an optical clock and an optical frequency comb via high fidelity optical frequency division, the resulting photonic microwave can surpass the performance of state-of-the-art microwave oscil-lators. It is crucial for the redefinition of the second to have lower phase noise and better stabil-ity microwave in order to preserve that timing from the optical to electronic domain. In this work, the performance of the generated photonic microwave is compared with that of a cryo-genic sapphire oscillator to evaluate the performance of a cavity-locked laser as an optical local oscillator.

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Precision measurement of the 176Lu+ 3D1 unperturbed microwave clock transition frequencies

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Poster session 1, April 21, 2026, 15:30 - 17:00

Optical frequency standards can have a significant quadrupole shift, especially for ion clocks which operate in large electric field gradients. To suppress this shift, the ^{176}Lu+ ($^3D_1$) optical standard averages over three hyperfine levels to realize a small residual quadrupole moment (RQM) of −2.54(25) × 10^−4 ea_0^2, which was determined through a combination of g-factor measurements and theory. Nonetheless, the quadrupole shift needs to be accurately assessed at the 10^-19 fractional uncertainty now being reached.

In this work, we accurately determine the unperturbed $^3D_1$ microwave transition frequencies through evaluation of the quadratic Zeeman shift and elimination of the quadrupole shifts by averaging over three orthogonal field orientations. We determine the two unperturbed microwave frequencies, f_1 = 10 491 519 945.228 82(38) Hz (F = 8 → F = 7) and f_2 = 11 290 004 289.881 61(36) Hz (F = 7 → F = 6). Consequently, these absolute frequencies can serve as a reference to infer the electric field gradient through measuring the microwave quadrupole shift.

The obtained accuracy of ~4 × 10^−14 allowed us to observe a deviation in the ratio of the microwave quadrupole shifts from that predicted by Clebsch-Gordan coefficients alone. We attribute this deviation to hyperfine-mixing and infer a RQM of −2.48(23) × 10^−4 ea_0^2. This result independently supports the evaluation of the quadrupole shift in the ^{176}Lu+ ($^3D_1$) optical standard.

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AQuRA, a prototype industrial transportable optical clock

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Poster session 1, April 21, 2026, 15:30 - 17:00

The AQuRA consortium gathers industries, universities and national metrology institutes. It's goal is to develop a European prototype of industrial transportable optical lattice clock, aiming for fractional instability and uncertainty of 5×10-18. We report on the design, assembly and integration of the clock modules, including the under vacuum strontium source, each of the laser sources and the optical distribution board, the stabilization system and the clock sequence control electronics. At the time of the writing, the first stage cooling of strontium was achieved.

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Miniature and chip-scale rubidium microwave atomic clocks: Industry trends and roadmap at Safran Timing Technologies

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Further developments of industrial miniature rubidium atomic clocks at Safran Timing Technologies are presented. Focus topics include reduction of power consumption and increased robustness.

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A Statistical Distribution Function for Laser Beatnote Linewidths

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Poster session 2, April 23, 2026, 15:30 - 17:00

We present a statistical distribution function as an accurate description of the statistical distribution of beatnote linewidths between two lasers. The distribution function reproduces the experimentally observed asymmetry and long-tail behavior with high precision, enabling the extraction of both the most probable beatnote linewidth and the individual linewidths of each laser. This approach provides a more comprehensive and reliable characterization of laser linewidth. With its simplicity and robustness, the distribution function offers strong potential as a practical, low-complexity alternative to the three-cornered-hat technique and provides valuable guidance for evaluating and optimizing ultra-stable laser systems.

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Timing Receiver Alternatives for NMIs

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Poster session 2, April 23, 2026, 15:30 - 17:00

GNSS together with TWSTFT are currently the only techniques used to link UTC(k) to TAI/UTC. During the 24th meeting of the CCTF, Session II at the BIPM Headquarters in Sèvres [1], two GNSS related recommendations were presented that address future changes of GPS signal provision and robustness of the NMI installations. This paper addresses the main aspects of those recommendations that a) recommend labs to operate and report data from three independent GNSS stations, and b) to start collecting and reporting data from GPS L1C, L2C, and L5 signals, to monitor and to analyze those signals and possible signal combination.
We present an overview of the currently used GNSS receivers and their relative performance and how suitable lower cost equipment performs as an alternative to legacy geodetic equipment, which is predominant in the NMIs. Cost effective options are desirable to facilitate three independent receiver chains at small or emerging labs. For example, the investigated Septentrio Mosaic-T is outperformed by its state-of-the-art sibling PolarX5-TR over all timescales. However, the performance penalty is negligible over typical integration times of one or five days. The iPPP performance of a short baseline common clock difference is below 1e-16 @ 1day MDEV and thus likely compatible with the requirements for a receiver contributing to TAI.
We also present ananalysis of the availability and performance of non-standard code combinations for CGGTTS using RISEGNSS, an open alternative provided by RISE [2]. C1C, C2C, C5Q observables in both single frequency use and dual frequency combination perform potentially better than the traditional semicodeless signals C1W and C2W considering the availability of the signals in the current GPS constellation. Typical performance of a short baseline common clock difference is better than 1e-15 @ 1day MDEV.

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Fibre-Optic Time and Optical Frequency Dissemination in a Single DWDM Channel using the Spread Spectrum Technique

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Poster session 1, April 21, 2026, 15:30 - 17:00

We will present a upgraded Spread Spectrum technique, that allows for real-time simultaneous time and optical frequency dissemination in a single DWDM channel over fibre. This technique has the advantage of secured and longer distance time transfer, simplified channel and device management, and improved optical frequency transfer performance.

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Triangle Connections Utilized for Distribution of White Rabbit in a Coherent Network Within Sweden

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[1]Netnod Ab

Poster session 2, April 23, 2026, 15:30 - 17:00

The study focuses on the White Rabbit (WR) profile transported in duplex format between the three largest cities in Sweden in the SUNET network, and a comparison between the duplex network and a bidirectional link network will be presented. The duplex network is configured in a triangle and each site is equipped with WR equipment and cesium atomic clocks. Transmission distances vary between sites, with the longest exceeding 690 km. Figure 1 presents an example how much a duplex WR connection between two cesium clocks varies over a period of more than 3 months. The fiber distance between the clocks exceeds 690km. For example The used equipment are of commercial type.

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Towards ground state cooled Coulomb crystals for clock operation with 10-19 systematic uncertainties and instabilities < 5×10-16/√(τ/1s)

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Poster session 2, April 23, 2026, 15:30 - 17:00

Optical clocks that are based on trapped ions offer a number of distinct advantages, including long trap lifetimes, low systematic uncertainty, and ease of operation. However, their statistical uncertainties are fundamentally limited by quantum projection noise (QPN). To suppress the QPN, a straightforward yet challenging approach is to operate with multiple ions rather than a single ion .
We developed a multi-ion optical clock using indium ions (115In+) that are sympathetically cooled by ytterbium ions (172Yb+). These ions are trapped in a linear Paul trap forming Coulomb crystals. We demonstrated clock operation with a 1In+-3Yb+ crystal with a systematic uncertainty of 2.5×10-18 and an instability of 1.6×10-15/√(τ/1s). Recently, we operated the clock with up to 20 ions, including 8 In+ clock ions and 12 Yb+ ions, with the instability below 6×10-16/√(τ/1s). The experimental data confirms the 1/√(N) scaling of QPN, where N is the clock ion number.
To increase the cooling efficiency, direct cooling of 115In+ on the intercombination line 1S0 – 3P1 at 230.6 nm will be added to sympathetic cooling. To further reduce systematic uncertainties and instability, we are performing spectroscopic characterization of the cooling process using the clock transition, in order to achieve:

- Understanding the cooling dynamics and final state for this unusual cooling regime, which is neither the resolved sideband cooling (strong binding regime) nor Doppler cooling (weak binding regime), because the intercombination transition has a natural linewidth of 360 kHz, comparable to the trap secular frequency.
- With direct cooling, crystal temperatures below 100µK, close to the ground state, are expected , which corresponds to a time dilation of less than 2×10-19, significantly reducing its uncertainty contribution.
- Increasing the clock ion (115In+) count whilst decreasing the sympathetic cooling ion (172Yb+) count for a fixed crystal size to suppress QPN. It is expected to reduce the instability below 5×10-16/√(τ/1s).

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Dark State Interference in Raman-Ramsey Coherent Population Trapping Clock: A Density Matrix Simulation Perspective

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Poster session 2, Atrium and B9, April 23, 2026, 15:30 - 17:00

The phenomenon of Coherent Population Trapping (CPT) is widely used for chip-scale atomic clocks. Alkali atoms like Rb and Cs exhibit multiple Zeeman sub-levels. This leads to multiple CPT resonances, depending on polarizations of the CPT fields and magnetic fields. They are best described using density matrix analysis of multi-level atom-light interactions. These CPT resonances cause interfering Ramsey fringes in Raman-Ramsey CPT (RRCPT), known as dark state interference. This results in magnetic-field-dependent oscillations in Ramsey fringe amplitude. Such effects have been observed in thermal vapors and cold atoms. They have been qualitatively explained using Zeeman shifts and Ramsey time.

Here, we present a density matrix treatment of an 11-level ^{87}Rb atomic system under Lin || Lin CPT fields in Raman-Ramsey interrogation. We quantitatively model the magnetic-field-dependent Ramsey fringes, their amplitude, and frequency shift. This reveals the interplay of first- and second-order Zeeman effects with Ramsey time. We further map the origin of these interferences to steady-state CPT resonances.

Additionally, we examine population dynamics to show the contribution of each Λ sub-system to the Ramsey fringes. Our framework quantitatively describes experimental results and provides deeper insights into RRCPT in multi-level atomic systems. It can also be extended to study perturbations in Ramsey fringe dynamics due to intensity imbalance, light shifts, etc., and for modeling the effects of stimulated Raman transition on CPT clock.

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Current Status Report of 171Yb Optical Lattice Clocks at KRISS

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Poster session 2, April 23, 2026, 15:30 - 17:00

Korea Research Institute of Standards and Science (KRISS) is actively developing ytterbi-um(Yb) optical lattice clocks as part of the global effort toward the redefinition of the SI second. Our first clock, KRISS-Yb1, has achieved a systematic uncertainty of 1.7×10^-17 and routinely contributes to International Atomic Time (TAI) and the realization of UTC(KRIS).
While KRISS-Yb1 offers stable operation, its initial design limits the systematic uncertainty to the low 10-17 level, primarily due to uncertainties in the BBR shift and the DC Stark shift. To meet the prerequisite of contributing to TAI at the < 2×10^-16 level for the SI second redefinition, the main challenge was minimizing the statistical uncertainty in the frequency chain to the hydrogen maser, requiring approximately 80% monthly uptime. Despite stable operation, the system's overall uptime was previously limited to around 50%.
The most critical factor affecting robustness of KRISS-Yb1 system was maintaining the cavity length stabilization for the optical lattice. Other factors included mode hopping of the ECDL for the clock laser and the stable beat note signal with good SNR between the clock laser and the optical frequency comb. To overcome the main limitation, we implemented a digital servo utilizing a FPGA for the cavity length control for the optical lattice. This upgrade successfully achieved an uptime of ~80% over 25 days of continuous operation, resulting in an uncertainty of 2.1×10^-16, as reported to BIPM Circular T 452. We expect to achieve uncertainties below 2×10^-16 by extending this operation period to 30 or 35 days. Furthermore, we plan to introduce this digital servo to other laser frequency and power stabilization systems to enhance long-term operational robustness.
Acknowledging the inherent systematic limitations of KRISS-Yb1, we are developing two new systems (KRISS-Yb2 and Yb3) with improved BBR shift and DC Stark shift uncertainties. We are currently evaluating their systematic uncertainties and expect to reach the mid 10^-18 level by the end of the year. Through continuous comparison with KRISS-Yb1, we also plan to identify any fre-quency differences beyond the expected system uncertainties that may not have been considered during development.

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Direct laser cooling of rubidium atoms using 420 nm blue light and its application in active optical clock

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Poster session 2, April 23, 2026, 15:30 - 17:00

Traditional rubidium cooling schemes typically employ 780 nm lasers, with cooling relying on the first excited state transition. In this work, we realize laser cooling of 87Rb atoms using the 6P3/2 high excited state with 420 nm blue light directly. This work breaks away from the traditional reliance on the 780 nm cooling transition (5S1/2→5P3/2) in rubidium atoms.

We generate a 3-W 420 nm blue laser and precisely lock its frequency to the 87Rb atomic transition 5S1/2 (F=2)→6P3/2 (F’=3). Experimentally, diffuse laser cooling technology is adopted, where a barium sulfate coating is used to construct an isotropic light field, allowing 87Rb atoms to experience effective Doppler cooling in any direction of motion. A cold 87Rb atom cloud with a length of up to one meter is prepared. Cold-atom absorption spectroscopy is performed using a 780 nm probe laser, and a distinct cold atom absorption peak is observed. The corresponding number of 87Rb cold atoms reaches 4.4×10^7, verifying the effectiveness of 420 nm blue-light laser cooling corresponding to the high excited state.

Under the current conditions, the number of 87Rb atoms cooled by 420 nm cooling is lower than that achieved with 780 nm cooling. On one hand, our cooling laser power has not yet reached saturation. On the other hand, during the 420 nm blue-light cooling process, a fraction of atoms decay into intermediate cooling states such as 4D3/2 and 4D5/2. However, cooling via the 420 nm high excited state offers a narrower natural linewidth (1.42 MHz) and a lower Doppler cooling limit temperature (approximately 34 μK), which implies that 420 nm cooling can achieve lower atomic velocities.

Furthermore, the 420 nm blue-light cooling technique shows potential for application in con-tinuous-wave active optical clock . In the cooling process, the atoms undergo spontaneous emis-sion to intermediate states before eventually returning to the ground state. This process not only realizes cooling but also ingeniously establishes population inversion, providing the necessary gain medium for active optical clock based on the 6S1/2→5P3/2 transition. In the future, we will further optimize the 420 nm blue-light cooling system to enhance the number of cooled atoms and cooling efficiency, thereby obtaining a more sufficient cold atom cloud to serve as the gain medium for active optical clock.

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Evaluation of an Additive Manufactured Microwave Cavity for Compact Cold-Atom Clock Studies

Miss Gabrijela Galic[1], Dr. Christoph Affolderbach[1], Prof. Gaetano Mileti[1], Prof. Paul Griffin[2], Prof. Erling Riis[2]
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Poster competition, April 21, 2026, 15:30 - 17:00

In view of the ongoing developments in the field of compact cold-atom clocks, we are working towards a highly compact cold-atom clock, based on laser cooling of 87Rb using the grating-Magneto-Optical Trap (G-MOT) approach that enables producing the cold atom sample directly inside a very small microwave cavity that is manufactured taking advantage of additive manufacturing techniques (Selective Laser Melting, SLM) of its most critical central part. In the first demonstration of this approach, one limitation to the clock performance is the Ramsey time limited to ≈ 10 ms, due to the cold atoms falling out of sight of the 4 mm transverse optical detection beam access.

To overcome this limitation, we present a new version of the microwave cavity that features four elongated side-holes enabling studies of the clock signal over a wider range of atomic fall heights along the cavity axis, towards Ramsey times up to ≈ 50 ms. The cavity incorporates four electrodes that establish a resonance at 6.835 GHz frequency, despite the small cavity dimensions of only ≈ 30 mm inner diameter. By adjusting the height of the cavity, the resonance can be tuned over ≈ 300 MHz around the desired 6.835 GHz frequency. An essential part of this study is the impact of the position of the coupling loop relative to the electrodes. We systematically tested various loop positions and analyzed their influence on coupling strength, full width at half maximum (FWHM), and quality factor of the cavity resonance. FEM simulations reproduce the cavity's essential microwave properties. Under good conditions we achieve ≈ -30 dB coupling efficiency (S11 parameter) along with a quality factor of around 800.

Comparison and Time Domain Evaluation of two GNSS TTS-4 Receiver Systems Referenced to a Common Cs Clock

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Accurate GNSS time-transfer plays a central role in maintaining national timescales, enabling re-liable participation in UTC, and supporting the operation of modern infrastructures that depend on precise synchronization. Even small, deterministic hardware delays within GNSS systems can introduce measurable offsets at the nanosecond level, which, if left uncharacterized, may propagate directly into the time scale. Therefore, it is essential to thoroughly evaluate the performance, stability, and behaviour of each receiver contributing to UTC(SASO) or any national realization of Coordinated Universal Time. In this work, we performed a detailed comparison be-tween two independent GNSS TTS-4 receiver systems, both referenced to the same Cs clock but using different antennas. The comparison revealed almost identical frequency drift behaviour for both receivers (–3.87 ns/day and –3.85 ns/day), confirming consistent long-term stability. A fixed time-scale offset of approximately 22 ns was observed between the two systems, attributable to known hardware contributions such as antenna delays, differences in cable lengths, propagation delays, internal receiver-processing delays, and the cable-delay difference between the Cs clock and each GNSS receiver all contribute to the observed offset. These delays vary over time due to temperature fluctuations, environmental electromagnetic effects, component aging, and other external influences. Such fac-tors cause small variations in the total delay of each signal path, which collectively manifest as the measured time-scale offset of approximately 22 ns. For better evaluate the performance of time domain difference, it is essential to study the variation using Allan variance. In GNSS time-transfer systems, white noise is typically expected at short averaging times, However, the presence of drift-like behaviour can indicate environmental influences such as temperature variations or thermal effects inside the receiver chain. Understanding these noise characteristics is essential when interpreting offsets between systems.

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Vibration Sensitivity Measurement of Ultra-stable Narrow Linewidth Lasers

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Abstract: Ultra-stable narrow-linewidth lasers, leveraging their exceptional frequency stability and ultra-narrow linewidth characteristics, enable the extraction of precise frequency information from atomic and molecular transition spectra[Milner, William R., et al. "Demonstration of a timescale based on a stable optical carrier." Physical Review Letters 123.17 (2019): 173201.]. They serve as a critical technology for realizing high-precision optical clocks. Currently, the Pound-Drever-Hall (PDH) technique is widely used to lock free-running lasers to high-stability Fabry-Perot (F-P) cavity[Eric D. Black; An introduction to Pound–Drever–Hall laser frequency stabilization. Am. J. Phys. 1 January 2001; 69 (1): 79–87]. F-P cavity's vibration is a key factor preventing many ultra-stable lasers from reaching their thermal noise limit. To address the challenge of measuring vibration sensitivity, this paper introduces a method which can achieve precise measurement of laser frequency. The first step of this method is to utilize another ultra-stable laser and employ the first-order sidebands generated by an electro-optic modulator to acquire the PDH error signal.The second step is to convent the voltage variation of the error signal into frequency variation through the frequency discriminator slope. The vibrational response of the vibration isolation table is quantified using an accelerometer. Measured via this method, the vibration sensitivities along the three orthogonal axes (x, y, z) are 4.71×10-10, 4.55×10-10, and 2.07×10-10, respectively. And the Allan standard deviation of frequency instability contributed by vibration noise is 9.17×10-17.
Keyword: Ultra-stable laser, F-P cavity, Vibration

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Designing low size cubic optical cavities

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Ultra-stable lasers are a critical enabling technology for a wide range of precision scientific instruments. The ultimate performance of systems such as optical atomic clocks, quantum computers and optical communication networks, amongst others, can be fundamentally limited by the frequency noise of the available lasers.

Numerous methods exist for pre-stabilising the frequency of a laser, but as interest grows in commercialising precision optical devices, so too does the importance of having portable optical frequency references. NPL has developed different versions of its patented cubic optical cavity for application outside of the laboratory, including deployment in space. Made from ultra-low expansion glass, and with symmetry in its geometry and mounting, the cubic cavity can be operated in any orientation (unlike many traditional static optical cavities) and can exhibit fractional frequency sensitivities to external vibration as low as 2.5×10^−11 g^−1 . Moreover, multiple optical frequencies can be stabilised using one cavity system, expanding the optical cavity’s capability and enabling novel features such as drift compensation. NPL has also developed bespoke digital electronics for locking multiple lasers to dual-axis cubic cavities for use in transportable optical clocks.

This thermo-mechanically insensitive design lends itself to applications where low size, weight and power (SWAP) are critical. NPL has worked extensively with the UK and European space agencies to develop this technology for use in space, and these cavity systems have undergone environmental testing (radiation, vibration and shock) across several ESA projects.

In this work, we present an exploration of the design space for small cubic optical cavities, investigating the limits possible for several applications when a minimal SWAP is required. In developing these systems, the team at NPL is targeting applications such as next-generation space-based Positioning, Navigation and Timing (PNT) networks, optical inter-satellite links, and the Next Generation Gravity Mission (NGGM).

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Rapid Measurement of the Zero-Expansion Temperature Point (T_0) in a 30cm-Long Optical Reference Cavity via Single Temperature Scan

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Abstract: The frequency stability of ultra-stable lasers depends critically on the length stability of optical reference cavities. Temperature variations cause thermal expansion of the cavity, leading to laser frequency drift . Operating ULE glass-based cavities near their zero-expansion temperature (T_0) minimizes this sensitivity . However, conventional steady-state measurement methods for T_0 determination in long, multilayer-shielded cavities require several months, limiting practical applications.
This paper presents a rapid measurement method using a single temperature sweep and introduces structural improvements to the system. Existing techniques typically place temperature sensors on outer shields and estimate T_0 through multi-parameter fitting, which is sensitive to model inaccuracies and parameter coupling. To overcome this, we implement a decoupled monitoring scheme: a heating film on the outermost shield provides global temperature control, while sensors mounted directly on the cavity base monitor local temperature near the cavity. This design enhances data reliability and fitting robustness.
Experiments using a 30 cm cavity with three-layer thermal shielding combined PDH stabilization and beat frequency detection to simultaneously acquire temperature and frequency data. Fitting based on ULE's thermal expansion characteristics yielded a T_0 of 34.81°C. Measurement time was reduced from several months to approximately ten days. The method significantly improves efficiency while maintaining accuracy, offering reliable support for thermal design and frequency stabilization of long ultra-stable cavities.

Keywords: Ultra-stable laser; Optical reference cavity; Zero-expansion temperature point; Single-scan measurement; Thermal shielding

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Design and development of the detection zone and state-selection cavity with coordinated optimization for a time-keep-ing 87Rb fountain clock

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Time-keeping 87Rb fountain clocks, utilizing laser-cooled atoms, are increasingly surpas-sing traditional cesium beam clocks and hydrogen masers in key performance met-rics, establishing them as a promising candidate for the next generation of time-keeping clocks1. They operate by launching cold rubidium atoms through a Ramsey cavity, where microwave in-teraction drives the atomic transition, followed by optical detection for frequency discrimina-tion.

A key design challenge lies in the sequential arrangement of the state-selection cavity and de-tection zone between the magneto-optical trap (MOT) chamber and Ramsey cavity. Sufficient separation between the two optical detection beams in the detection zone is essential to prevent optical detection crosstalk and ensure accurate atomic transition probability measurement. However, conventional designs face a trade-off: increasing detection spacing extends the atom-ic flight path, reducing the returning atomic number and potentially degrading the signal-to-noise ratio.

This work presents an optimized design that resolves this conflict. The detection zone features a 45 mm separation between detection laser beam centers—30 mm wider than conventional set-ups—effectively eliminating crosstalk. The state-selection cavity, with an internal height re-duced by 29 mm to 28.61 mm and a diameter of 83.28 mm, maintains a loaded Q-factor of 2205 while operating 876 kHz from the atomic resonance. This co-design satisfies state-selection re-quirements without extending the atomic flight path to Ramsey cavity, thereby preserving the signal-to-noise ratio while meeting the performance demands of time-keeping 87Rb fountain clocks.

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Development of an optical two-photon clock for space

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Here, we present our development of an optical clock based on a monochromatic 87Rb two-photon reference operating at 778.1 nm with the goal of a one-year long in-orbit demonstration in low Earth orbit. The payload consists of a hermetically sealed, micro-integrated ECDL at 778.1 nm with integrated amplifier, an EOM, an additional semiconductor amplifier, a Rb two-photon spectroscopy module and a space qualified frequency comb. The payload and its constituents are designed to be operated in vacuum and need to withstand quasi-static loads of 15 g, random vibrations up to 10 g, shocks of more than 1000 g and large temperature variation associated with the space mission.

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Stable Frequency and 100G/s data transmission through ur-ban underground optical fiber

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Stable frequency standards have important applications in gravitational wave detection, precise navigation timing, and verification of relativity principles. Effectively utilizing the present fiber network resource to construct the stable radio frequency (RF) transfer system has been explored by many researchers. However, there are various data services in optical fibers used for communication, which can have an impact on stable frequency transmission. The sideband energy of the data signal leaks into the wavelength of the frequency signal, resulting in an increase in the phase jitter of the fre-quency signal. The nonlinear interaction of signals at different wavelengths generates new fre-quency components and interferes with the original signal. Meanwhile， the low-frequency com-ponent of the intensity modulation signal may leak through the photodetector into the phase-locked loop (PLL), introducing low-frequency phase noise. It is interesting to make the frequen-cy transfer compatible with the existing communication data through a reasonable structural de-sign.
In this paper, we demonstrate simultaneous transmission of a stable frequency signal with 100G/s data through a 68.6 km urban fiber link. The experimental results show that the communication data does not affect our proposed system with frequency instability of 2.5E-14@ 1 s and 7.2E-16@ 1000 s. Our study may be useful for the construction of frequency transmission net-works based on existing optical fibers.

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Locking a Chip-scale Laser to an Air-gap Optical Reference Cavity Based on an Optoelectronic Oscillator

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Miniaturized low-noise optical frequency references play a vital role in fields such as optical atomic clocks, frequency combs, and photonic microwave generation. In this work, based on op-toelectronic oscillator (OEO) locking technology, a chip-scale self-injection-locked distributed feedback (SIL DFB) laser is locked to a high-finesse air-gap Fabry–Pérot (FP) optical reference cavity with a volume of less than 10 mL. By beating this laser with a higher-performance ultra-stable laser and applying feedforward processing of the OEO loop signal, the resulting beat note exhibits a phase noise lower than -66.3 dBc/Hz at a 10 kHz offset and an optical domain stability of 1.73×10^-12 at 0.1 s. This work provides strong support for the development of low-noise, min-iaturized, integrated, and low-power optical frequency references, with promising applications in ultra-low noise microwave synthesis and related fields.

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Phase Stabilization of 780 nm Diode Lasers for Application to Atom Interferometry

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Atom interferometry plays a critical role in the cutting-edge quantum sensors and experiments in gravimetry, inertial navigation, and fundamental research. These advanced technologies rely on highly stable and narrow linewidth lasers to coherently control and manipulate atomic wave packets1. In a typical quantum gravimeter, 87Rb atoms are first cooled and trapped inside an ultrahigh vacuum system using magneto-optical trapping with a magnetic field gradient of 12 Gauss/cm. After laser cooling and trapping, a key step in the atom interferometer sequence is the generation of Raman beams for the coherent manipulation of atomic states through two photons stimulated raman transitions. These Raman transitions form the core of atom interferometer and implemented in the sequence of Mach Zehnder configuration consisting of (π/2, π, π/2) pulses. The first π/2 pulse split the atoms into coherent superposition of two atomic quantum states, the subsequent π pulse swaps them, and another π/2 pulse recombined the atomic wave packets, enabling interference2. During free fall, the two atomic pathways accumulate a relative phase shift proportional to acceleration due to gravity (g) which is extracted through laser induced fluorescence techniques in quantum gravimeter. For such precision measurements, the generation of Raman beams involves use of phase stabilized diode lasers, realized using beat frequency generation.

In this study, phase stabilization of two 780 nm lasers essential for the Raman beam generation to perform atom interferometry is presented. One extended cavity diode laser (ECDL) is fre-quency stabilized to the hyperfine saturated absorption transition of 87Rb (F = 2 → 3') D2 line. The frequency stabilized laser beam serves as optical reference and is combined with another 780 nm ECDL to generate a heterodyne beat frequency signal3. The resulting beat note signal is detected at 120 MHz and used as RF input to an optical phase locked loop. A stable 120 MHz reference signal generated by function generator is simultaneously provided to the phase lock-ing system to ensure phase synchronization between the two lasers.

The present implementation involves the 120 MHz offset frequency, enabling the system vali-dation using readily available reference source. Direct locking at ground state hyperfine splitting of 6.834 GHz requires an ultra-stable microwave reference which is currently under devel-opment in our setup. Therefore, 120 MHz locking scheme serves as an intermediate step to validate the system and ultimate objective is to extend this system to 6.834 GHz for atom interfer-ometry in 87Rb quantum gravimeter.

Design and Characterization of Silicon Microresonators for Advanced Sensing Applications

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Ultrastable laser sources are a crucial tool in frequency metrology, especially in areas such as precision spectroscopy and optical clocks, with further applications in telecommunications, aerospace and sensing. In general, these out-of-the-lab applications also have critical requirements in terms of size, weight and power consumption; from this perspective, the miniaturization of laser sources is a matter of interest.
One way to realize miniaturized ultrastable laser sources is through high-quality-factor microfabricated Silicon Nitride resonators, that can be used as a reference for semiconductor laser stabilization. As part of the SENSEI project, INRIM is developing a chip-scale low-noise laser stabilised onto a Silicon Nitride resonator for sensing applications. To reduce power consumption and footprint, the laser stabilisation relies on self-injection lock by the resonator backscattered radiation, instead of more conventional active stabilization schemes. In our case the resonator is based on a spiral geometry. The main advantage of this choice over conventional ring-shaped geometries is the increase in the resonator length, which leads to a lower thermal noise while maintaining a small footprint. However, preserving high quality factors over long resonator lengths requires addressing intrinsic loss mechanisms such as material purity, bending and sidewall scattering. We designed several representative resonator geometries that allow characterization of individual loss mechanisms and fabricated them in the Piquet nanofabrication facility at INRIM. This characterization allows the design of spiral resonators that balance intrinsic loss with thermal noise properties, targeting a phase noise <100 rad^2/Hz at 10 Hz for the stabilised resonator, which is suitable for sensing applications.
In this work we will present the microresonators design strategy, the characterization of their intrinsic losses and corresponding quality factor, and their thermal noise properties, as well as the characterization of the on-chip laser system.

1367 nm Rb active optical clock signals based on diffuse laser cooling

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Active optical clocks (AOCs), which are realized by coherent stimulated emission, have two advantages of suppression of the cavity-pulling effect and narrow linewidth. Compared to thermal atomic systems, the use of laser cooling can reduce Doppler broadening and collision broadening, thereby narrowing the gain linewidth. Moreover, diffuse laser cooling technique in a long bar-shaped integrating sphere can avoid the influence of magnetic fields and easily prepare a cold atom cloud on the meter scale, which is of great importance to realize cold-atom AOC.

For Rb four-level AOCs, during the cold atom preparation and the AOC signal detection, the 780 nm cooling light not only induces a light shift in the lower energy level 5P3/2 of the clock transition in the active optical clock but also pumps a large number of atoms to the 5P3/2 energy level, preventing the population inversion between the 62S1/2 and 52P3/2 energy levels. To maximize the performance of the AOC and avoid the influence of the cooling and repumping lasers, the experiment employs a pulsed cooling scheme, separating the cold atom preparation and the detection of pulsed signals. The preparation of cold atoms is first completed within a 1500 ms period. Then, during a subsequent 100 ms period, a high-power 420 nm fiber laser locked to the hyperfine transition line of 87Rb atoms for 5S1/2(F=2)→6P3/2(F=3) is used for pumping to achieve the output of a 50 ms pulsed AOC signal.

We prepared a cold rubidium atomic ensemble with an 25 μK temperature , approximately 30 ms lifetime and optical depth greater than 4, which was used as the narrow-bandwidth gain medium for AOC. Ultimately, under 420 nm laser pumping, a superradiant signal at 1367 nm with a total power exceeding 3 μW and a duration of about 50 ms was achieved without a resonant cavity. This scheme avoids the influence of cooling light on the energy levels related to the clock transition. Furthermore, the central frequency of the cavityless AOC 1367nm output is unaffected by cavity pulling effects. In subsequent work, we will further optimize and improve the power and performance of the superradiant 1367 nm signal, and measure the linewidth and stability.

Upgrade of REFIMEVE network for low-noise long-distance frequency transfer

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Fiber-based optical frequency and time transfer has led to significant advances in precision measurements and has extended its impact to other disciplines, such as quantum communica-tions or Earth sciences . The REFIMEVE network, led by Laboratoire de Physique des Lasers (LPL) and Laboratoire Temps Espace (LTE), which spans all over France, combines long-distance transfer capabilities with state-of-the-art performance, achieving frequency instability and inaccuracy levels as low as 10^{-19}. As shown on Figure 1, it has been extended to south of France and is now reaching around 9000 km of optical fiber links, with a full network supervi-sion and a real-time assessment of the stability and accuracy of each link. REFIMEVE current-ly provides frequency and time references from the French national metrological institute, LNE-OP, to more than 30 laboratories in France and to CERN, and ensures clock comparisons in Europe .
The latest results demonstrated the achievement of simultaneous phase-coherent transfers at the fundamental limit, exhibiting a record long-term instability of 10^{-21} to the best of our knowledge. These state-of-the-art performances have been successfully demonstrated in indus-trial Multibranch Laser Stations. We are presenting the ongoing integration of these MLS and ultra-stable lasers into the REFIMEVE network. We have already deployed MLS at some of the key-nodes of the network, allowing us to coherently disseminate the REFIMEVE optical signal to several labs, making large-scale, correlated measurements of fundamental effects possible. Cavity-stabilized lasers are planned to equip a few locations in the network as a clean-up opti-cal oscillator of the residual phase noise accumulated on long-haul optical links. It will both enhance the cascaded link performance and operation, and restore the linewidth of the dissemi-nated signal, which can broaden up to a few kHz for averaging time of 100 ms for links of length >100-1000 km . It addresses a crucial need for exploiting the REFIMEVE signal in spec-troscopy and radio-astronomy applications and for supporting the foreseen development of a continental-scale frequency transfer network.

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Enabling Future Distributed Sensing Applications through Quantum Time Transfer

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Quantum Time Transfer (QTT) uses entangled photons and quantum communication protocols to synchronize distant clocks with picosecond-level precision and high resilience. Unlike classical RF-based methods, QTT is inherently resistant to atmospheric delays, interference, and jamming.
This capability enables a new generation of distributed sensing systems, where large-scale sensor arrays—spanning Earth observation, climate monitoring, and geophysical mapping—require precise temporal alignment to correlate weak, spatially distributed signals. By establishing a unified temporal framework, QTT enhances coherence, sensitivity, and data integrity across networks of sensors or satellites.
Recent simulations and hardware demonstrations show that QTT maintains timing stability within a few picoseconds over fibre and satellite links, even under realistic noise and loss conditions. These results highlight QTT's transformative potential for quantum-enhanced Earth observation, secure communications, and high-precision scientific measurement.

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Mid-10-15 Stability Optical Cavity in a Sub-Liter Passive Vacuum Chamber

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Ultra-stable lasers (USL) are essential components for many quantum technologies ranging from optical clocks to quantum computing, as well as optical communication, microwave sources and RADAR applications . The USL spectral purity usually originates from the length stability of an ultra-stable cavity. These rely conventionally on large, actively pumped vacuum chambers. The complexity added by this in terms of form-factor, stray magnetic fields and high-voltage supplies is not suited to the operational conditions required by many in-field applications.
We present an USL system with a stability of σADEV = 4×10-15 at τ = 1 s in an unprecedented form-factor using under 1 l for the vacuum system and < 1.5 l for the complete package, com-prising the required in-coupling and modulation (Pound-Drever-Hall) optics. The main enabling step in miniaturization is the use of a passive getter pump that, after initial activation, maintains an ultra-high vacuum for an estimated 6-10 years within the chamber. The latter contains two compact temperature shields to minimize the impact of environmental temperature variations. The optical cavity itself features a tetradecahedron ultra-low expansion (Corning ULE®) glass spacer and mirrors designed by Menlo Systems. The cavity is held rigidly by mechanical supports that have been optimized to minimize the vibrational and acoustic sensitivity of the cavity length, but also enable transportability.
The USL system enables the construction of an Ultrastable Microwave System in a 3 height-unit rack together with a frequency comb and all necessary electronics to port the USL spectral purity from the optical to the microwave domain. A thorough analysis of the USL system performance has been undertaken.We will present the system architecture, theoretical estimations and comprehensive measure-ments of all relevant metrological properties.

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Transient sensitivity of optical atomic clocks and prospects for active-clock–based detection schemes

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Optical atomic clocks are widely used to search for temporal variations of fundamental constants. Their response to rapidly evolving signals is fundamentally limited by the dynamics of the feedback loop stabilizing the laser to the atomic transition. In this work, we analyze how the servo bandwidth, gain, and operational mode shape the observable signature of short-lived perturbations. Our model reveals that in passive optical clocks, transient events with duration comparable to the loop response time can be significantly suppressed, which directly impacts the attainable sensitivity in correlation-based searches.

Motivated by these findings, we investigate the potential of active optical clocks, whose lasing mechanism inherently reduces the role of tight servo control. We show that active clocks can preserve sensitivity to short-term disturbances, making them promising instruments for probing rapid or stochastic variations of fundamental constants. The results highlight a qualitative difference between passive and active architectures and support the development of next-generation active-clock platforms. Updated analytical expressions accounting for servo effects are provided, and previously published estimates are revised accordingly.

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Improvements to the uncertainty evaluation of NPL-Sr1

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In this poster we present recent improvements to the evaluation of the black-body radiation (BBR) shift of a ^{87}Sr optical lattice clock, NPL-Sr1, through exploiting in-situ thermometry that has brought its total uncertainty to < 4 x 10^(-18). Alongside improvements to NPL's ^{171}Yb+ (E3) optical ion clock, recent measurements between the two systems have achieved a total measurement uncertainty of the Yb+/Sr optical frequency ratio at ≲ 5 x 10^(-18).

We also present ongoing work to further improve the NPL-Sr1 uncertainty budget through a new in-vacuum lattice cavity. The removal of hot spot formation on the view ports will mean the uncertainty from the BBR shift evaluation will no longer dominate and we anticipate to be next limited by lattice light and density shifts. The design of the new lattice cavity will enable large trapping volumes and deep potential wells for efficient atom loading, allowing for exploration of regimes of very low trap depth to reduce contributions to the total inaccuracy from lattice light and density shifts, aiming to bring the total uncertainty towards 1 x 10^(-18).

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Optical Pointing Compensation under Atmospheric Turbulence for Free-Space Frequency Transfer

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We propose a receiver-side active optical pointing compensation system for free-space frequency transfer, based on image-guided fast-steering control. Experiments over a 200-m link show that the method effectively suppresses turbulence-induced beam wander, the RMS of the electrical power fluctuation measured by the PD without compensation is 17.69, while it decreases to 9.64 with adaptive compensation. and achieving a fractional frequency stability of 1.89×10^-12@1s.

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An interim active fibre-stabilisation and frequency distribution system for SKA-MID commissioning

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The Square Kilometre Array will rely on exceptionally stable reference signals to coordinate its large distributed arrays, with SKA-MID drawing its master references from an ensemble of hydrogen masers located inside the Central Processing Facility. These maser signals drive the telescope frequency reference and are distributed through fibre links to the telescope infrastructure. Environmental disturbances acting on the fibre introduce phase fluctuations that reduce frequency stability and degrade coherence across the array. The full telescope will address these effects using actively stabilised frequency transfer, ensuring that each antenna receives a clean phase reference suitable for high precision interferometry. While the final central equipment for this system is undergoing manufacture and verification, an interim configuration is required to sustain the instrument development schedule and allow receiver commissioning to proceed without delay.

The interim solution is provided by the iCE, a compact eight channel transmitter assembly that supports reference distribution to the eight receiver modules located on the dishes. This arrangement enables the first SKA dishes to begin system level testing while the long baseline frequency distribution hardware continues its development pathway. The iCE produces phase corrected optical tones that the receiver modules track in order to generate their required internal phase-stablised reference frequencies. By supplying a stable reference to a small but representative subset of receiver modules, the iCE gives the engineering teams a controlled environment for validating interface behaviour, confirming synchronisation performance, and exercising the broader Synchronisation and Timing subsystem.

A central design objective for the iCE is rapid deployability. To achieve this, the system is built predominantly from commercial off the shelf components, which reduces development overheads and ensures short lead times for replacement and assembly. This approach yields a cost effective and modular design that can be reproduced and expanded as needed. It does, however, introduce trade offs: the physical footprint is larger than that of the final central equipment, and certain full system requirements are only partially met. These limitations are acceptable for the interim role, which focuses on short to medium length fibre spans and early system validation rather than long haul distribution across the entire array.

Despite its simplified construction, the iCE achieves the performance needed for operational testing on fibre links up to eight kilometres. The system maintains uptime above 99% and residual timing jitter <35 femtoseconds. These metrics confirm that the reference delivered to the receiver modules remains sufficiently clean to support stable frequency synthesis and early telescope operation. The interim configuration is now active on site and is driving the first two operational SKA-MID antennas, with first light targeted for December 2025. It will remain in place until the final central equipment becomes available in 2027. Although it is not suitable for long distance distribution without amplification, the iCE provides a reliable, accessible, and modular bridge solution that preserves commissioning momentum and establishes a strong foundation for the full Synchronization and Timing system.

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Hybrid optical lattice clock without a cavity

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[1]Vector Atomic

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We present a new approach to operation of an optical lattice clock where a production Iodine clock is used to simplify the system and enable robust operation.

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Comparative Study of SESAM-Mode-Locked All-Fiber Erbium Oscillators: Cavity-Dependent Stability and Soliton Dynamics

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Poster session 2, April 23, 2026, 15:30 - 17:00

We compare three SESAM-mode-locked all-fiber Er-doped optical oscillators (two linear cavities with intracavity/extracavity WDM and FBG end mirror, and one ring cavity) to reveal how cavity architecture governs pulse evolution, noise, and long-term stability. Single-shot dispersive Fourier transform tracks the transition from Q-switching to stable soliton operation. The extracavity-WDM linear design minimizes thresholds but sacrifices stability, whereas the ring cavity provides the broadest spectrum, highest RF SNR, confirmed soliton dynamics, and <5% power drift over 48 h, offering clear guidance for optimizing ultrafast oscillators for time-frequency and sensing applications.

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Ultra-stable laser with a frequency instability of 1×10^{-16} at room temperature

Mr. Weinan Zhao[1]
[1]Birmm

Poster session 2, April 23, 2026, 15:30 - 17:00

Ultra-stable lasers play an important role in optical atomic clocks, time-frequency transfer, gravi-tational wave detection, and fundamental physics experiments. Typically, the optical path for ul-tra-stable lasers is built using free-space optical components. This work present an ultra-stable laser with the optical path constructed by all-fiber optical components, demonstrating the effi-ciency and stability of the fiber optic setup. We designed an optical reference cavity with a 30 cm long crystal-coated mirror, compensating for the thermal expansion of the FS substrate using ULE ring. The precise temperature control is conducted with the three-layer thermal shielding structure. The time constant was measured to be 10.5 days. Through a single measurement meth-od, the zero thermal expansion temperature was measured to be 35°C in several days. By beating with two other reference lasers using three-corner hat method, the frequency instability was found to reach 1.3 × 10^(-16) at an integration time of 1s.

301

Passive suppression of residual amplitude modulation noise in all-fiber optical path for ultra-stable lasers

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Residual amplitude modulation (RAM) noise is one of the key factors limiting the performance of ultra-stable lasers. Its primary sources are twofold: the birefringence effect of the electro-optic modulator and parasitic etalon effects in the optical path. In this paper, we have developed a PDH reflection optical path using all-fiber optical components and employed a multi-axis ad-justment stage to enable direct laser coupling. We investigated the residual amplitude modulation noise introduced by the fiber-optic path and identified its main source as parasitic´etalon effects. This effect also increased the system's sensitivity to vibrations. To mitigate this, we adopted an integrated module design that allows for the packaging and fixation of the fiber-optic path, min-imizing relative motion between the optical path and the cavity. This approach enabled passive suppression of the residual amplitude modulation noise, successfully reducing it from 2×10^{-15} to 4×10^{-16}.

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Long-term Performance of Iodine Absorption Cells

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Poster session 1, April 21, 2026, 15:30 - 17:00

Molecular iodine (127I2) absorption cells serve as optical frequency references for laser stan-dards and molecular optical clocks, with applications in various fields, including space re-search, time and frequency metrology, and metrology of length. The spectral properties of the cell fundamentally limit the long-term frequency stability and accuracy of these standards. Fused silica, the standard material employed for cell fabrication due to its optical quality and chemical inertness, exhibits a relatively high permeability to helium. Over extended operatio-nal periods, the diffusion of atmospheric helium through the cell walls into the hermetically sealed volume results in contamination of the iodine environment. This helium diffusion in-duces collisional broadening of the iodine hyperfine transitions and pressure-induced frequency shifts, thereby degrading the spectral properties of the reference and compromising the long-term stability of the laser/clock.
This paper reports on the development and experimental evaluation of iodine absorption cells equipped with protective shielding designed to mitigate helium permeation. To quantify the efficacy of the shielding and investigate the long-term impact of helium diffusion on iodine spectral profiles, a comparative study was conducted between standard fused silica cells and the newly developed shielded cells. To simulate long-term ageing effects within a feasible ex-perimental timeframe, both cell types were installed in a controlled chamber and subjected to an overpressured helium environment to accelerate the diffusion process.
The evolution of the iodine transition parameters was monitored utilising two complementary high-precision spectroscopic techniques. Laser-Induced Fluorescence (LIF) measurements were performed to assess the collisional quenching and broadening mechanisms, with the resulting data evaluated using the Stern-Volmer formalism. Simultaneously, absolute frequency shifts and spectral profile variations were interrogated via saturated absorption spectroscopy. The spectroscopy setup utilised a frequency scanner based on a narrow-linewidth fibre laser, which was locked to a referenced optical frequency comb. The experimental data obtained from the accelerated ageing process were correlated with theoretical diffusion models to quantify the permeation kinetics.

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The Galileo Iodine Clock

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We present the development of an iodine-based optical clock for satellite navigation as part of the Galileo/EGNOS Upstream R&D program, funded by Horizon Europe and coordinated by the European Commission (DG DEFIS). The clock uses a laser stabilized to an iodine transition via modulation transfer spectroscopy and a frequency comb to bridge optical and microwave domains. Designed to withstand launch stresses and operate reliably in the harsh space environment under the stringent constraints of a satellite platform, it targets a stability below 1×10^-13 per square root of tau and a performance level in the low 10^-15 range per day. The project is currently in the engineering model phase.

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Impact of Inter-modal Coupling and Mismatch on the Blue-Sideband Excitation in Coupled MEMS Resonators

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The abstract shows an investigation of the frequency comb phenomena within a coupled MEMS resonator device, to better understand the conditions under which these combs are generated. We use blue-sideband excitation in order to couple the modes of interest, and then characterize the effect of inter-modal energy coupling strength and ampliude ratio on the threshold amplitude for blue-sideband excitation. We show that frequency combs can be generated using this approach and that a weak coupling regime is required for combs to occur under blue-sideband excitation based approaches.

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Multi-electrode Magnetron-Type Cavity for Rb cell Clocks

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Poster session 2, April 23, 2026, 15:30 - 17:00

We presented a design of magnetron-type MW cavity based on multi-electrode for vapor-cell rubidium atomic clocks. This cavity makes the structural assembly more flexible and can pro-vide a highly uniform MW field distribution, which can be used to construct high-performance, compact vapor-cell atomic clocks.

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Dual-Mode PMUT Resonator for Glucose Sensing at Physiologically Relevant Concentrations

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Poster session 2, April 23, 2026, 15:30 - 17:00

This work demonstrates glucose detection in the physiological blood range (2–20 mM) using a dual-mode Piezoelectric Micromachined Ultrasound Transducer (PMUT) that integrates both resonant self-sensing and through-transmission (Tx/Rx) operation on the same membrane. Unlike existing ultrasound-based liquid sensors , which are limited to sucrose or high concentration solutions , our platform demonstrates sub-millimolar resolution across the full clinical range relevant to diabetes monitoring, offering a potential pathway toward non-invasive biochemical sensing using MEMS resonant technology.
The PMUT is fabricated via the PiezoMEMS process with a 500 nm AlN layer on SOI and a trench-backed membrane. A split top electrode (175 × 350 µm) enables dual-mode operation. In resonant mode, the frequency shifts from 460.8 kHz (DI water) to 466.3 kHz at 20 mM glucose (+5.4 kHz, ~188 Hz/mM), with a measured quality factor of Q = 9.2. Noise analysis (σ_{MAD} ≈ 154 Hz) gives a 0.67 mM detection limit, below the Hypoglycemia threshold. Fixed-frequency phase interrogation (460.8 kHz) shows linear mapping (R^2 ≈ 0.93) with 0.08–0.11 mM resolution. In Tx–Rx mode, group delay rises from 0.8 µs to 4.8 µs, and attenuation (Δα) reaches +5 dB at 20 mM. These results support multi-parameter sensing, with Δf_0 tracking density and Q/attenuation capturing viscosity and acoustic impedance.
To our knowledge, this is the first MEMS ultrasound-based glucose sensor to cover the full clinical blood concentration range using purely acoustic measurements, paving the way toward miniaturized resonant biochemical sensing.

314

Setup and performance of resilient reference timing services at Jammertest 2025

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Poster session 1, April 21, 2026, 15:30 - 17:00

We present setup and performance data for reference timing generation and distribution to Jammertest 2025. Jammertest is a 5 day long open-air GNSS interference (jamming, spoofing, meaconing) exercise arranged by Norwegian authorities since 2022 at Bleik/Andøya in northern Norway. Undisturbed and accurate reference timing is needed for organizers to create credible coherent spoofing signals synchronized to actual GNSS satellite signals and for test particpants to measure the effect of broadcast GNSS interference scenarios on GNSS timing devices. We describe progress in providing a comprehensive environment for testing the resilience of multi-source (GNSS, PTP, physical timing signals) timing devices.

315

Frequency Dissemination Using Brillouin Amplification

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Poster session 1, April 21, 2026, 15:30 - 17:00

Frequency dissemination is a key component in optical-frequency metrology, enabling the transfer of highly stable laser signals between remote locations for applications in atomic timekeeping, geodesy, and fundamental physics. To achieve long-distance dissemination, optical amplification is required to maintain sufficient signal intensity for reliable transmission. For phase-noise compensation, these amplifiers are incorporated into a Michelson interferometer usually operating in a bidirectional mode. Our previous setup has used two bidirectional Erbium-Doped Fiber Amplifiers (EDFAs) but found to exhibit intensity instability when operated at high gain. Alternatively, narrowband Brillouin amplification can provide high gain, particularly for weak input signals.

In this work, we demonstrate an interferometric frequency dissemination setup employing one bidirectional EDFA and one unidirectional higher gain Brillouin amplifier.

Using the current configuration we have distributed a phase-stable optical frequency to the remote station, letting it propagate back to transmitting end, achieving an Allan deviation below 2×10^(-18) after 100s.

316

Towards Continuous Operation of an ISI 40Ca+ Optical Clock System

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Poster session 2, April 23, 2026, 15:30 - 17:00

We present the $40Ca^+$ optical clock developed at the Institute of Scientific Instruments (ISI), emphasizing stable, near-continuous operation. The system combines frequency-stabilized lasers, a linear Paul trap, and digital control hardware, supported by an automated relocking and ion-recovery framework that prevents ion loss and restores optimal conditions without operator intervention, achieving over 90% uptime.

To minimize downtime, a fully remote ion-reloading procedure enables single-ion loading in under five minutes and allows the clock to resume operation within approximately 30 minutes if the ion is lost. Undesired additional ions can be rapidly removed via RF-trap adjustments, further shortening recovery time.

Clock operation is continuously monitored through a Grafana-based system that records laser, trap, and environmental parameters in real time, with automated alerts for deviations to enable rapid operator response. While the system demonstrates strong robustness, it currently lacks active compensation for environmental drifts, such as pressure or magnetic-field fluctuations, which can affect long-term stability.

This work represents a significant step toward continuous $40Ca^+$ clock operation and establishes a foundation for further automation, including fully automatic ion reloading and environmental stabilization at ISI.

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Frequency Detuning and Self-Recovery Stabilization Control System for the 87Rb Atomic Fountain Clock

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Poster competition, April 21, 2026, 15:30 - 17:00

The atomic fountain clock serves as a high-precision time-frequency reference and has significant applications in atomic timekeeping, high-precision navigation, geodesy, and fundamental physics research1-4. Laser cooling technology is essential for the operation of atomic fountains, with the stability of the laser frequency being critical for the cooling system of the rubidium atomic fountain clock5. This paper discusses the requirements for laser frequency stability and rapid large-range detuning during the cooling and launch phases of the rubidium-87 atomic fountain clock. And develops a frequency detuning and self-recovery laser frequency stabilization control system using a commercial 1560 nm fiber laser in combination with modulation transfer spectroscopy technology. The system ensures laser frequency stability. The system utilizes FPGA technology to process error signals at high speed and employs a "forward-backward-forward" triple scan pre-locking method to suppress the impact of piezoelectric ceramic magnetic hysteresis on lock point accuracy. The laser frequency is locked to the hyperfine spectral line 52S1/2 F=2→52P3/2 F´=3 of the 87Rb atomic D2 line via PI feedback control. Additionally, the system integrates TTL trigger signal detection, frequency detuning, detuning delay, and self-recovery locking functions for the sub-Doppler cooling process, allowing for precise large-range frequency detuning and rapid re-locking. Allan variance results indicate that the system’s short-term frequency stability is 1.52×10-11@10s, and its long-term stability exceeds 1.56×10-11@200000s. The system’s single-cycle detuning time is 106 ms, with stable re-locking achieved at trigger intervals of 2 s and 5 s. The frequency detuning exceeds 140 MHz, satisfying the detuning requirements for the cooling and launch phases of the rubidium-87 timekeeping fountain clock.

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New calcium optical frequency standard characterization in comparison campaign

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Poster session 1, April 21, 2026, 15:30 - 17:00

This report presents the characterization and performance assessment of a novel optical frequency standard based on a single trapped 40Ca+ ion, developed at the Institute of Scientific Instruments of the Czech Academy of Sciences (ISI CAS). Preliminary results demonstrate favorable frequency instability and an absolute frequency determination that aligns with values reported by international groups and CIPM recommendations, thereby validating the standard's operation. In addition to establishing a comprehensive uncertainty budget, the standard was benchmarked during a comparison campaign conducted in late 2025 involving three reference optical clocks based on the 171Yb+ E2 transition. These references included the transportable "Opticlock" from the Physikalisch-Technische Bundesanstalt (PTB) for local assessment, as well as remote standards at the Austrian Federal Office of Metrology (BEV) and the Czech Metrology Institute (CMI) connected via optical fiber links. The confirmed mutual consistency of these 171Yb+ standards provided a robust reference frame, facilitating the first high-precision, direct measurement of the 171Yb+/40Ca+ frequency ratio.

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Towards V-UV countinuous-wave laser source for precision time and frequency metrology

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We are developing a continuous-wave V-UV laser source for Al^+ (167 nm) and Th (148 nm) optical clocks using second-harmonic generation in periodically poled $BaMgF_4$ (BMF). Domain inversion will be achieved by high-voltage pulses applied to a structured chromium electrode, fabricated via electron-beam lithography lift-off on in-house polished BMF. The lithography process is complete, and poling and SHG testing will follow shortly.

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Time and Frequency Activities at Justervesenet

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Poster session 1, April 21, 2026, 15:30 - 17:00

The time and frequency laboratory at Justervesenet (Norway) generates and disseminates the time scale UTC(JV). We describe the current overall design of the timescale generation chains, performance of time scale generation and work in progress to improve the metrological performance and technical reliability of systems.

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Dynamic weighting of local regression models in automatic clock steering algorithms

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Poster session 2, April 23, 2026, 15:30 - 17:00

Based on recent work on the automatic steering of UTC(JV), a framework for automatic clock steering algorithms based on dynamically weighted local regression models is presented. The system considers a dynamically weighted local regression model of UTC-UTC(k) time series that combines the predicted results from several sources using an inverse-covariance weighting scheme.

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Testing GNSS interference in a fully operating digital substation

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Poster session 2, April 23, 2026, 15:30 - 17:00

Testing GNSS interference can be a challenging task, particularly for larger systems that cannot easily be broughtto test environments like e.g. Jammertest. Here we tested different GNSS interference scenarios in a fully operating digital substation. For the testing we used a software based GNSS simulator connected in line between the substation GNSS antenna and the substation clocks. The setup enables simulating true GNSS signals synchronized to the actual satellite signals received by the antenna, in combination with interference signals generated in the GNSS simulator.

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Implementation of a Phase-Coherent Fiber Infrastructure for Optical Clock Comparisons Across CMI, CESNET, ISI, and BEV

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Poster session 2, April 23, 2026, 15:30 - 17:00

We present a phase-coherent optical fiber network that supports multiple intranational optical clock comparison campaigns linking CMI, ISI, and BEV. The network has been established through collaboration between CESNET, ISI, CMI, BEV, and TU Wien. CESNET provides the long-haul fiber infrastructure connecting the participating institutes, while ISI implements active phase stabilization to maintain coherent optical frequency transfer within the Czech Republic and across national borders. The stabilized links are designed to achieve a target fractional frequency instability at the 10^-18 level over typical campaign durations. CMI participates with its $171Yb^{+}$ optical clock, connected through a dedicated stabilized link. ISI operates its $40Ca^{+}$ optical clock within the Czech part of the network. BEV hosts a $171Yb^{+}$ optical clock procured by TU Wien, functioning as a cross-border comparison site.
This contribution focuses on the fiber infrastructure, stabilization schemes, and implementation challenges of a multi-institutional network for optical frequency transfer. We describe methods used to preserve phase coherence over long distances, the architecture of the network, and approaches for integrating multiple stationary and transportable clocks across different sites. The setup provides a framework for frequency dissemination and for future continuous cross-border optical clock comparisons between Czechia and Austria.

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Optical-injection based dual-frequency generator for compact CPT atomic clocks

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Poster competition, April 21, 2026, 15:30 - 17:00

We demonstrate a compact dual-frequency and dual-polarization laser source based on optical injection of COTS DFB lasers for compact and high-performance coherent population trapping Cs atomic clocks. The optical injection locking loop is optimized to achieve a phase coherence with RF phase noise reduction by 100 dB at 10 kHz offset from the carrier frequency, i.e., 9.2 GHz. The proposed architecture eliminates optical delays between the Master and the Slave lasers and incorporates simplified optical phase-locked injection loops. Ongoing improvements include work on the mechanical integration and the frequency and intensity locking loops for clock operation.

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Local Oscillator Breadboards for Space Radio Interferometry

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Poster session 2, April 23, 2026, 15:30 - 17:00

Space radio interferometry aimed at imaging black holes requires an Allan deviation better than 3e-13/tau (assuming WPN) beyond 450 s. Individual spaceborne oscillators, however, typically sustain such stability for only about 10 s. To bridge this gap, we investigate two-way optical frequency transfer (OTWTFT). The key innovation is the use of the ESA OTWTFT patent , which enables mission-critical frequency stability while significantly reducing the system complexity by eliminating the need to measure and correct the differential Doppler from the inter-satellite links. Because the patented method synchronizes the sum of the oscillator frequencies, it is dubbed Upper Sideband Synchronization (USBS).

Two LO architectures (P1 and P2) were breadboarded and tested in the ESTEC Microwave Laboratory. We report their measured performance, which is driven by the characteristics of the microwave mixers, the selected USBS architecture, and the phase noise of the core oscillators. The use of high-speed photodiodes is promising to eliminate passive microwave frequency multipliers. The achieved Allan deviation complies with the mission requirements with a margin, including at zero frequency offset. We also demonstrate stable operation using identical microwave tones modulated onto the optical carriers. Long-term phase-difference measurements show no ramp, indicating excellent stability on multi-week timescales and suggesting the potential to further relax phase-calibration needs.

Environmental tests covered a ±3 °C temperature range at an orbital period of 4.5 h. The resulting technology readiness level (TRL) from the breadboarding campaign is assessed as TRL 4. The next step is an instrument-level demonstration.

Towards Large Scale White Rabbit Network

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Poster session 1, April 21, 2026, 15:30 - 17:00

CESNET, the Czech National Research and Education Network, provides high capacity Internet connectivity to 26 universities and 57 Academy of Sciences institutes. Since 2010 the network is used for high precision time and frequency transfer, enabling atomic clock comparisons across dif-ferent institutions. We are now extending this capability by deploying White Rabbit technology, which delivers sub nanosecond synchronization and sub picosecond jitter. The network will consist of 17 nodes across the country, with two hydrogen masers serving as time sources.
Currently, there is a small part of the distribution network deployed, a loop between Prague and Ivančice, measuring 498 km, deployed on standard commercial fiber, using a total of 5 custom bi-di amplifiers. Since the network formed a loop, both the master and a slave node could be located at the same place and their time offset could be measured using a time interval counter. A diagram of the network can be seen on Fig. 1.

This experiment has shown big promise, since even without any calibration, its time offset was just 1.6 ns and TDEV roughly 10^-11 up to averaging interval of 10^4.
In this poster we will present our experience with deploying and operating a White Rabbit network of national scale. During the trial period in first quarter of 2026, we will measure the performance of the system in metrics such as TDEV. We will also test the network for its robustness in case of a link or device failure, using failover to backup time sources. We are currently developing a com-plex monitoring solution for the network, gathering metrics from all of the WR switches, which we will also test and report on during this trial period.

Monitoring of GNSS timing performances by GEMOP

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Poster session 2, April 23, 2026, 15:30 - 17:00

We present the work carried out in the frame of the GEMOP (Galileo and EGNOS Monitoring Of Performances) about the independent assessment of the Galileo timing performances. These performances are compared to the Galileo Open Service Service Definition Document Minimum Performance Levels, and to GPS, GLONASS and BDS-3 whenever possible. Each partner (CNES, ORB, RISE, ROA and INRiM) makes use of its own time-calibrated station to produce key performance indicators, monthly collected and merged by CNES.
We focus here on the GST offset to UTC, the UTC time and frequency dissemination accuracies, the GGTO accuracy, the availability of GAUT and GGTO, the BGD accuracy and the performances of on-board clocks.

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Precise Time Calibration and Deployments of White Rabbit Switches for T-REFIMEVE

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Poster session 1, April 21, 2026, 15:30 - 17:00

Accurate time and frequency transfer is essential for various applications including time and frequency metrology, and advanced scientific research such as high-energy physics, astronomy, quantum telecommunications. In France, the REFIMEVE infrastructure, led by Laboratoire de Physique des Lasers (LPL) and Laboratoire Temps Espace (LTE), distributes ultra-stable optical frequency signals generated by LNE-OP at LTE, Observatoire de Paris to more than 30 laboratories via the RENATER fiber network. The ongoing T-REFIMEVE project extends this capability to precise time and microwave frequency transfer by integrating a White Rabbit (WR) network over unidirectional fiber links, targeting a time transfer accuracy below 10 ns level across more than 80 WR nodes interconnected over 5000 km of optical fibers network.

To achieve this accuracy, it is essential to calibrate both instrumental and propagation delays. We present the methodology and realization of a test bench developed to calibrate instrumental delays of several tens (i.e., batch of 10) of White Rabbit Switches (WRS) in parallel before their deployment in the field. The calibration has been performed by following CERN guidelines and EM-PIR/VSL best practices, using unidirectional SFP transceivers at 1560.61 nm. An independent calibration chain was established at LTE, where one of specific WRS port 1 was selected as Golden Calibrator and its egress and ingress delays were determined following the calibration guide. Using the Golden Calibrator, a back-up calibrator port 1 was calibrated. After that, the back-up calibrator (port 1) was used to calibrate ports 2 to 18 of the first WRS, which is now called as Golden Calibrator WRS. This switch has been used to calibrate one port of each of the 10 WRS under calibration in parallel. The calibration process was automated by developing a Python-based WRS calibration software, which borrows heavily from CERN's calibration code. The time offset between the Golden Calibrator WRS and Back-up Calibrator WRS improved from 55 ps (σA = 39 ps) before calibration to –11 ps (σA = 14 ps) after calibration. We will also report preliminary data for the deployed WRS including stability results for a 300 km unidirectional link in the REFIMEVE network, demonstrating the robustness of our calibration approach for time dissemination over large scale (5000 km) networks.

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A unified PTP link calibration model under IEEE Standard 1588-2019

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Precision Time Protocol (PTP) is a packet-based network protocol that enables accurate and precise clock synchronization in distributed systems. Since IEEE Standard 1588-2019, a High Accuracy (HA) profile based on White Rabbit (WR) implementation, referring to as WR-PTP, has been added to PTP v2 standard as an extension. To achieve the enhanced clock synchronization accuracy, WR-PTP calibration methods have been deeply investigated as part of WR technology. However, the calibration model of the regular PTP devices (PTP devices which are incompatible to HA profile) hasn't been fully investigated to the best of the authors' knowledge, which would limit the evaluation method and precision to the PTP link. In this paper, we propose a unified PTP link calibration model which is compatible with both regular PTP devices and WR-PTP devices under IEEE Std 1588-2019. In the proposed calibration model, we first identify the asymmetry sources in a PTP link and then calibrate contributions from each source. In the PTP device calibration model, we propose a PTP device model which connects timestamp format and pulse format. This model characterizes the internal functional structure of PTP devices and serves as an extension to the current WR device calibration model. For the transmission medium calibration, we have developed a new calibration kit, independent of WR-PTP devices, for accurate calculation of transmission medium delays. Finally, the calibration results of PTP devices, with an uncertainty of 20 ns, will be presented in this paper.

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Refining the reference time of IGS real-time products for PPP one-way timing

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Thanks to the contribution of International GNSS Service (IGS), the real-time (RT) precise orbit and clock products are widely used for PPP time transfer. However, the time deviation between the reference time of RT products and UTC(k) could reach several or even tens of nanoseconds. Although the reference time of the IGS precise clock products can be eliminated in PPP time transfer, it provides a time reference for one-way timing. As a result, the existing IGS RT products are not available for the accurate, stable and traceable timing service.
To address the demand for PPP one-way timing, this contribution proposes a method to refine the reference time of RT precise clock products. Firstly, the clock comparisons between the satellite clocks and the hydrogen atomic clocks of IGS stations are calculated using PPP time transfer. Then the Kalman time scale algorithm is adopted to generate a free-running time scale with the clock comparison results. Finally, the free-running time scale is steered to UTC(PTB) by the Linear Quadratic Gaussian (LQG) algorithm, developing a new time scale to replace the original reference time of RT products.
In our experiment, ten IGS stations equipped with hydrogen atomic clocks were used to refine the GPS and BDS-3 reference time of CNES RT products. Then the original and corrected RT products were applied for PPP one-way timing in five timing laboratories. The receiver hardware delay involved in time scale steering and PPP one-way timing was calibrated with the reference value provided by BIPM. The results show that the RMS value of GPS timing results with refined products could reach 0.45 ns, 0.11 ns and 1.73 ns referring to UTC(ORB), UTC(PTB) and UTC(USNO), respectively. We conclude the bias of the timing results referring to UTC(USNO) was related to the uncertainty of the calibration value. Although the BIPM currently does not provide calibration value for Beidou B1I and B3I signal, we could evaluate the variation of the BDS-3 timing results. The STD value of BDS-3 timing results with refined products could reach 0.53 ns, 0.40 ns and 0.72 ns referring to UTC(ORB), UTC(PTB) and UTC(USNO), respectively.

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Building blocks for mmWave 5G and 6G Infrastructure time and frequency synchronization

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For several years, Creotech Instruments S.A. has been developing key components to enable the adoption of the White Rabbit solution in telecommunication infrastructure such as 5G and 6G, Time as a Service, and Quantum Key Distribution. Our work has highlighted some missing elements in the existing WR infrastructure.
One of the most dynamically developing areas is currently 5G mmWave private networks. This opinion is also shared by ESA, which enabled the creation of the WR5G project. The research and development efforts focus on synchronizing 5G Radio Access Network components provided by MicroAmp using the White Rabbit technology.
As an answer to the specific 5G/6G needs, we have developed a low-cost, versatile WR Node dedicated to synchronizing and connecting existing non-WR infrastructure. Our design is a low-cost two-port WR switch based on Artix-7 series FPGA with an onboard 6.4 GHz fully synchronized LMX2572 RF synthesizer and a remote management board.
The new node is a single device providing sub-nanosecond time and frequency synchronization, as well as IP connectivity to devices such as oscilloscopes, RF analyzers, data acquisition systems, etc. Our design can operate as a standalone device or as a PCI Express Network Card with White Rabbit and PCIe Precise Time Measurement (PTM) capabilities.
We have successfully implemented time and frequency synchronization between a GPS reference source and a 5G OpenRAN server, achieving time synchronization better than 15 ns between the GPS reference and the 5G Radio Unit.
The new solution is currently in the manufacturing and testing phase of the second prototype. The first prototype has proven capable of meeting the current and future requirements of 5G and 6G networks, as well as those of other applications demanding precise and reliable time and frequency reference distribution. Its unique features enable infrastructure to be scaled seamlessly while ensuring compatibility with devices that rely solely on PTPv2 and SyncE. The new WR node will be commercially available next year.
The project will also verify the extension of the mmWave 5G private network with NTN, such as Starlink or OneWeb, providing a scalable solution with high throughput (multi-gigabit per second) and low latency.

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Characterisation of a Lab-based Strontium Optical Lattice Clock

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Poster session 1, April 21, 2026, 15:30 - 17:00

Strontium optical lattice clocks are leading candidates for contributing towards the redefinition of the second . This is due to its highly desirable doubly forbidden clock transition, which allows for a very narrow linewidth and a high Q factor – directly related to the clock's stability. With the capabilities of reaching instability levels of 10^(-16)or better, this allows us to use these devices for applications such as telecommunications, radar and geodesy. The lab-based system at the University of Birmingham aims to develop a high-performing clock with an uncertainty on the order of 10^(-18).

A preliminary systematic evaluation of the system running with strontium-88 has been undertaken including an initial simulation of the blackbody radiation shift as shown in Figure 1, this demonstrated a gradient across the system between the ambient temperature and 723K internally (the oven) and 450K (Zeeman window heat band) externally, these values lead to a shift of 2.33(±0.02)Hz with a full systematic evaluation currently underway. The system has demonstrated its capability to run continuously for a long period of time and a measurement campaign in collaboration with National Physical Laboratory (NPL) is planned to take place in early 2026.

The lab-based clock represents a major milestone as it is the first running strontium optical lattice clock at the University of Birmingham and the only operational system in the UK outside of NPL. The system not only acts as a long-term, high accuracy reference for the Alkaline group but also contributes to the redefinition of the second through planned participation of measurement campaigns.

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Measurement validation and cycle slip detection on a single optical frequency comb

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Stable, accurate, and traceable frequency reference signals are critical for the academic and industrial development of precision timekeeping technologies, with applications in telecommunications, navigation, finance, and the energy sector. This is of particular import with the development of next-generation atomic reference standards based on optical transitions, which are now reaching record precision at the 18th decimal place . The attainment of such precision is enabled through the use of optical frequency combs, extending primary microwave frequency standards into the optical domain .
To ensure and maintain trust in the results produced, ongoing validation of frequency and phase measurements can be crucial, as a single cycle slip within an hour of measurement can cause a bias on the measured frequency on the order of 10-18, if undetected and unaccounted for . The ideal validation would involve an out-of-loop secondary comb measurement used to verify each data point ; however, this is often unfeasible or unpractical. Alternatives involve counting several known optical frequency ratios, which requires access to several stable frequency standards, using multiple independent tracking oscillators to detect cycle slips or employing redundant counting, which can both increase experimental complexity.
Here we present an investigation into the relationship between signal-to-noise ratio (SNR), and the rate of cycle slips as well as the offset this introduces against a second frequency comb per-forming the same measurement. With this we present an investigation into the efficacy of two different validation schemes that can be deployed with a single comb: using continuous SNR monitoring as a predictor for likely cycle slip events in both counting and locking electronics and employing a double counting scheme on all frequency signals to detect uncommon cycle slips in the counting electronics. In unideal SNR conditions we find double counting to offer an effective tool for validation of frequency data, provided the availability of multiple filters of different bandwidths covering the desired frequencies, however this can lead to unaccounted errors which may be caught by SNR tracking.

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Integrated Si3N4 high Q Microring Resonatorsfor Optoelectronic Oscillators

Mr. Zeeshan Ahmed

Poster competition, April 21, 2026, 15:30 - 17:00

Optoelectronic Oscillators (OEOs) are used to generate spectrally pure microwaves frequencies with low phase noise. Conventional OEOs are bulky with the use separate elements for the laser, the modulator, the fiber optic delay line, the photodiode and the electrical amplifier. For that, integrated optoelectronic oscillator are a promising option in order to reduce the footprint . One of the space consuming and environment sensitive element is the fiber optic delay line that can be replaced by an integrated microring resonator providing a high Q factor. The approach we are exploring is based on a directly amplitude modulated single mode laser chip butt-coupled to a Si3N4 chip integrating a high Q ring resonator (Fig. 1). The work presented here is on the choice of the optimal circuit in terms of Q factor depending on the ring design parameters.

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NOVEL HAMMER-SHAPED ELECTRODE DESIGN FOR XBAR (HXBAR) Q ENHANCEMENT

Mr. Federico Peretti

Poster competition, April 21, 2026, 15:30 - 17:00

Thin film LiNbO3 resonators are fundamental for current and next generation RF filters. In recent years, XBARs have gained a lot of interest because they can attain high frequencies and coupling, while retaining a significant Q. However, it remains a constant challenge to suppress spurious modes and to increase Q. To address this, different electrode layouts have been proposed, such as trapezoidal, and checker-shaped. However, all these solutions remain at the lay-out level, and the cross-sectional shape of the electrodes remains rectangular.
This work introduces an innovative hammer-shaped electrode XBAR resonator (HXBAR) that constitutes a departure from the classical cross-section. The proposed geometry minimizes mechanical displacement within the metal layer, which leads to a reduction of acoustic energy losses and of spurious modes. At the same time, the structure can be made thick, thus maintaining a low electrical resistance, thereby contributing to an improvement in the quality factor (Q).

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Memristor-like Resonant MEMS Accelerometer

Mr. Ryan Leatherbarrow

Poster competition, April 21, 2026, 15:30 - 17:00

We present, for the first time, the observation of cross-domain pinched hysteresis in the amplitude-stiffness response of a resonant MEMS accelerometer. Pinched hysteresis is the hallmark characteristic of a memristor, a key building block for in-sensor computation systems and energy-efficient edge AI. Unlike memristors, which have an electrical domain input and output, the pinched hysteresis within the resonant MEMS accelerometer has a physical domain input and an electrical domain output, demonstrating that resonant MEMS sensors can be utilized for in-sensor computing devices, offering sensor-integrated sensing, memory, and computing capabilities.

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Ultra-low phase noise RF synthesis for Cs CPT atomic clock interrogation with an optoelectronic oscillator

Mr. Jimmy Pennanech

Poster competition, April 21, 2026, 15:30 - 17:00

Atomic clocks based on coherent population trapping (CPT) and operating with a Ramsey pulsed optical interrogation sequence of the RF hyperfine transition demonstrated impressive frequency stabilities of a few 10^{-13} at 1 s. In this pulsed interrogation scheme, the atomic clock becomes sensitive to the phase noise of the optically carried RF signal through the so-called Dick effect. This work describes a simple frequency synthesis to generate a RF local oscillator at 4.596 GHz whose estimated contribution to the relative frequency instability of the clock is 3×10^{-14} at 1 s.
We propose to use a 10 GHz OEO as the reference frequency instead of a low frequency OCXO. The OEO is carefully designed to exhibit ultra-low phase noise at low offset frequencies (-103 dBc/Hz at 100 Hz offset). The OEO then drives a frequency divider-by-2 on one side, and a digital synthesis on the other, which offers the required agility for Ramsey interrogation. The recombination provides the 4.596 GHz local oscillator for Cs interrogation with state-of-the-art phase noise performances.

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Progress on miniaturized laser-cooled 171Yb+ ion microwave clock

Miss Ying Zheng

Poster competition, April 21, 2026, 15:30 - 17:00

The ytterbium ion microwave clock, benefits from technologically mature and highly stable laser systems, offering a distinct advantage in the development of compact, integrated, and transportable microwave frequency standards. This paper presents the progress on miniaturized laser-cooled 171Yb+ ion microwave clock in Tsinghua University. The volume of the physical package is integrated to 47.09 L. The measured short-term frequency stability of the clock reaches $1.1\times10^{-12}/\sqrt{\tau}$, surpassing results previously reported by the National Physical Laboratory (UK) and the National Institute of Information and Communications Technology (Japan).

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Development of an additively manufactured compact cold-atom fountain clock

Mr. Samuel Smith

Poster competition, April 21, 2026, 15:30 - 17:00

Here we present recent progress toward developing a compact cold-atom microwave fountain clock based on a grating MOT (gMOT) and an additively-manufactured microwave cavity. These components aim to simplify the overall system complexity and bring the design closer to a mass-producible clock. We discuss the clock's design and preliminary performance and highlight recent improvements intended to enhance both short-term and long-term stability.

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Pinched Hysteresis within 1:1 Coupled MEMS Resonator

Mr. Ang Li

Poster competition, April 21, 2026, 15:30 - 17:00

We show for the first time that a 1:1 coupled MEMS resonator device can be used to observe a cross-domain pinched hysteresis in the amplitude response, which is a hallmark characteristic of a memristor. This shows great promise for further research into coupled resonator memristor-like devices, which are ideally placed to be used as a key component for in-sensor computing, neuromorphic computing and AI hardware. This is achieved by coupling the intrinsic resonant modes of the device, without the need for nonlinear operating schemes such as parametric modulation, which has been shown previously.

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Sub-attosecond Optical Frequency Transfer via Photonic Integrated Interferometer

Mr. Ziang Qiu

Poster competition, April 21, 2026, 15:30 - 17:00

We report an ultra-compact photonic integrated interferometer based on thin-film lithium niobate (TFLN) platform for two-way optical frequency transfer (TW-OFT). Through compact waveguide integration and stringent out-of-loop path matching, the proposed system effectively suppresses non-reciprocal, environment-induced phase noise, while significantly enhancing the system instability and accuracy. Over a continuous 48 hour measurement, the integrated interferometer exhibits sub-attosecond level time error and a short-term instability of 8.48×10-20 at 1 s, approaching the fundamental electrical noise limitation. Furthermore, it displays an exceptionally low sensitivity to ambient fluctuations, manifesting a phase-temperature coefficient of only 0.037 as/K, representing the best reported result to date. This work provides an effective technical pathway toward the development of miniaturized and large-scale networked optical frequency transfer systems.

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Transportable 171Yb Lattice Clock for Metrology and Geodesy

Mr. Eric Swiler

Poster competition, April 21, 2026, 15:30 - 17:00

Optical lattice clocks (OLCs) are among the best clocks in the world, offering fractional systematic uncertainties below the 1×10-18 level and able to average into the low 10-18 decade in under an hour. Fielding this level of performance in a transportable OLC is crucial for intercontinental optical frequency comparisons required for the redefinition of the second and enables direct measurements of the geopotential difference between two sites via the relativistic redshift of the clock frequency (relativistic geodesy).
We have developed a transportable 171Yb OLC targeting these metrological goals. Our system consists of four 19-inch racks: two for controllers, lasers, and the atomic physics package; one for the cavity stabilized clock local oscillator; and one for our optical clockwork comb. We expect total systematic uncertainty of 4.1×10-18, with leading uncertainty contributions from lattice Stark shift (3.5×10-18) and blackbody radiation (1.7×10-18).
Uncertainty budgets are necessary for high performance clocks, but true out-of-loop validation of clock performance requires rigorous comparison. To this end, we have moved the transportable clock (NIST-YbT) to the nearby University of Colorado Boulder campus and compared to the stationary clock at NIST (NIST-YbI) over ~3 km of fiber. We have also deployed NIST-YbT to the observatory atop Mt Blue Sky (~4300 m elevation) for a preliminary remote systems test, set-ting the stage for a future relativistic geodesy campaign via comparison to NIST-YbI using a combination of free-space and fiber time transfer.

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Real-time measurement of the tidally induced geopotential changes via optical clocks

Mr. Kilian Stahl

Poster competition, April 21, 2026, 15:30 - 17:00

Optical lattice clocks offer the lowest instabilities of any existing frequency standards, reaching $\sigma_y < 1\times10^{-16} (\tau/s)^{-1/2}$. This enables fast frequency comparisons reaching 1×10^{-18} uncertainty within few hours. Optical interferometric fibre links enable such comparisons across continents with no loss of stability for these averaging times, allowing the comparison of lattice clocks at remote locations and the observation of variations of geopotential differences in real time.
We report on comparisons of various stationary and transportable lattice clocks across four in-stitutes in Europe, involving PTB, INRiM, LTE and NPL during the year 2025. In particular, the PTB transportable clock Sr4 was operated at INRiM in Torino, Italy and compared to the sta-tionary clock Sr3 at PTB in Brunswick, Germany over a period of several days in March of 2025. The observed frequency ratio clearly resolves the variation of the geopotential difference, which is caused mainly by tides. We compare this and other measurements to the predictions from tide models. These demonstrations show that international clock comparisons have reached a level of stability where time-dependent variations can not only be resolved but need to be considered during data analysis, e.g., aliasing induced by interruptions in the operation of the clocks or links at similar time scales.

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Impact of an optical redefinition of the SI second on the international time scales TAI and TT(BIPM)

Ms. Roxanne Siadat

Poster competition, April 21, 2026, 15:30 - 17:00

Recent progress in optical frequency standards has laid the groundwork for a redefinition of the SI second based on one or multiple optical frequency atomic transitions. Optical frequency standards have evaluated uncertainties around 100 times lower than the microwave frequency caesium fountain primary standards which currently realise the definition of the second. The Consultative Committee for Time & Frequency (CCTF) has laid out several criteria which must be met before a redefinition - currently targeted for 2030. These criteria aim to ensure the maturity of the technology at the point of redefinition and to maintain consistency with the previous definition. Criterion I.4 concerns the contribution of optical frequency standards to International Atomic Time (TAI) as secondary frequency standards, placing minimum constraints on contributions from state-of-the-art optical frequency standards and requiring checks that there should be no degradation to TAI if it were calibrated by optical standards.

We have carried out the first evaluation of the impact of an optical redefinition of the second on TAI and on the BIPM's realisation of Terrestrial Time, TT(BIPM). For a single transition (Option 1) definition, each of ^{87}Sr 5s^2 $^1S_0$ – 5s5p $^3P_0$, ^{171}Yb 6s^2 $^1S_0$ – 6s6p $^3P_0$ and ^{171}Yb+ 6s ^{2}S1/2 – 4f^{13}6s^2 ^{2}F7/2 were considered in turn as the defining transition. These were selected based on availability of data from past TAI contributions. The optimised frequency values for secondary representations of the second were recalculated in each scenario, following the methodology used in recent updates to the BIPM's list of recommended frequency values. The uncertainties on these values are part of the input to the TAI and TT(BIPM) algorithms. The case of a definition based on an ensemble of transitions (Option 2) will also be considered at the conference.

Using the updated uncertainties on the recalculated optimised frequency values, we have simulated the evaluation of the frequency of TAI with respect to TT(BIPM) - referred to as 'd' in Circular T. We have compared 'd' and its uncertainty to the current definition case for each potential optical definition case, allowing us to estimate the impact of an optical definition of the second on TAI and TT(BIPM). By analysing the number of optical frequency standards contributing to TAI and TT(BIPM) in each period, their uncertainties, and therefore their weights in the algorithms, we can provide an assessment of the requirements on optical contributions to TAI to ensure there is no degradation to TAI or its uncertainty in the case of a redefinition. The result is in agreement with the relevant redefinition criterion and is an indicator of the progress needed for an optical definition of the second.

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High-pulse-energy integrated mode-locked lasers enabling on-chip supercontinuum generation

Mr. Zheru Qiu

Poster competition, April 21, 2026, 15:30 - 17:00

A fully integrated frequency comb featuring an octave-spanning spectrum and an electronically detectable repetition rate has long been sought for its potential to enable chip-scale optical atomic clocks and low-noise microwave generation via optical frequency division. Here, we demonstrate the first wafer-scale fabricated photonic integrated ultrafast mode-locked laser capable of generating pulses with energies exceeding 1 nJ on-chip, as well as generating a octave spanning supercontinuum in another waveguide directly. We believe this may open a new path for an integrated self-referenced frequency comb for timing applications.