UNIVERSITY *of* York

EFTF

European Frequency
& Time Forum 2016

# 30th European Frequency and Time Forum

4th - 7th April 2016, York, United Kingdom

# Welcome to EFTF-2016 at the University of York


We are delighted to welcome you to the 30th European Frequency and Time Forum (EFTF), being held, for the first time, at the University of York in the UK from 4th to 7th April, 2016. This continues the series of successful meetings that started in 1987.

The tutorials, technical sessions, keynote presentations, invited speakers and exhibits will cover the many aspects of the very active field of Time & Frequency.

As usual, the three Committees have joined their efforts to organise the event: the Local Organising Committee (LOC), the Scientific Committee (SC) and the Executive Committee (EC).

The **Local Organising Committee** of EFTF-2016 includes representatives from the University of York, the UK National Physical Laboratory (NPL), the UK and France. We acknowledge the strong support from NPL for funding the EFTF awards and many companies for taking on Exhibitor Stands which are essential for an event that will bring together over 300 people for scientific, social and friendly meetings during the whole week.

The **Scientific Committee** of EFTF-2016 has arranged a rich scientific programme resulting from 228 submitted abstracts. The schedule includes three parallel sessions of lectures, poster sessions on Tuesday and Wednesday afternoons and a short presentation from each exhibitor on Wednesday morning. The poster papers will be displayed during the whole duration of the conference

This year, we are very pleased to announce, that the two Tuesday morning plenary talks will be given by **Professor Andrew Lyne**, Emeritus Professor of Physics at the University of Manchester and former director of the Jodrell Bank Observatory and **David Rooney**, Curator of Time, Navigation and Transport at the Science Museum.

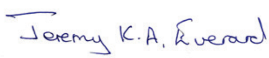
**Professor Lyne's** talk is entitled: **'The formation, life and uses of pulsars - nature's finest cosmic clocks'** and **David Rooney's** talk is entitled: **'Selling time: Stories from the Greenwich Observatory'.**

We are indebted to all the members of the SC and in particular the six group chairs: Alexandre Reinhardt, Jean-Pierre Aubry, Stefan Weyers, Svenja Knappe, Pierre Waller and Helen Margolis.

The **Executive Committee** of EFTF is very pleased that scientists, students and professionals meet once more and take this unique opportunity to learn, to exchange and to present their latest scientific and technological achievements to the community. We are particularly grateful to our members who organised the tutorials (Gaetano Mileti), the EFTF awards (Pierre Waller), the exhibits (Wolfgang Schäfer), the student poster competition (François Vernotte) and to the sponsors who have enabled a strong student travel support programme once again this year. We are also pleased that EFTF represents an occasion for several other committees, working groups and project consortia, from CCTF, EURAMET, and other organisations, to convene in splinter and satellite meetings.

We would like to wish you a motivating and inspiring forum.

Kind regards,



| | | |
|---|---|---|
| Jeremy Everard | Pascale Defraigne | Ekkehard Peik |
| Chair of the | Chair of the | Chair of the |
| EFTF 2016 LOC | EFTF 2016 SC | EFTF 2016 EC |

# Contents

# GENERAL CONFERENCE SCHEDULE

**Sunday Apr 3rd**

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|---|---|
| 17:00 - 19:00 | Registration – James College Reception |

**Monday Apr 4th**

| | |
|---|---|
| 08:00 - 18:00 | Registration - Exhibition Centre |
| 08:30 - 18:00 | **Tutorials in P/L001 and P/L005** |
| 18:00 - 20:00 | **Welcome Reception - Exhibition Centre** |

**Tuesday Apr 5th**

| | |
|---|---|
| 08:00 - 18:00 | Registration |
| 08:40 - 10:40 | **Invited Plenary Speakers, P/X001**<br>**Andrew Lyne**<br>'The formation, life and uses of pulsars - nature's finest cosmic clocks'<br>**David Rooney**<br>'Selling time: Stories from the Greenwich Observatory' |
| 10:40 - 11:10 | Coffee / tea break |
| 11:10 - 12:30 | **Lecture Sessions A1**<br>A1L-A: Timescales and SI Second, Room P/X001<br>A1L-B: Cold Atoms for Sensors and Clocks, Room P/L001<br>A1L-C: Piezoelectric Resonators I, Room P/L002 |
| 12:30 - 14:00 | Lunch Break |
| 14:00 - 15:40 | **Poster Sessions A2**<br>A2P-D: Student Paper Competition, P/L005<br>A2P-E: Frequency References and Measurements, Poster Area<br>A2P-F: Piezoelectric Resonators II, Poster Area<br>A2P-G: Microwave Frequency Standards & Applications I, Poster Area<br>A2P-H: Timekeeping, Time & Freq Transfer, GNSS Apps I, Poster Area<br>A2P-J: Optical Frequency Standards & Applications I, Poster Area |
| 15:40 - 16:00 | Coffee / tea break |
| 16:00 - 17:40 | **Lecture Sessions A3**<br>A3L-A: Lattice Clocks I, Room P/X001<br>A3L-B: Space Applications, Room P/L001<br>A3L-C: Sensors, Room P/L002 |

**Wednesday Apr 6th**

| | |
|---|---|
| 08:00 - 18:00 | Registration |
| 08:40 - 10:00 | **Lecture Sessions B1**<br>B1L-A: Quantum Measurement, Room P/X001<br>B1L-B: GNSS and Applications, Room P/L001<br>B1L-C:Cross Correlation, Room P/L002 |
| 10:00 - 10:40 | **Exhibitors' Presentation (P/X001)** |
| 10:40 - 11:10 | Coffee / tea break |

| | |
|---|---|
| 11:10 - 12:30 | **Lecture Sessions B2**<br>B2L-A: Applications of Optical Frequency Standards, P/X001<br>B2L-B: Atomic Magnetometers and Their Applications, P/L001<br>B2L-C: Advances in TWSTFT, P/L002 |
| 12:30 - 14:00 | Lunch Break |
| 14:00 - 15:40 | **Poster Sessions B3**<br>B3P-E: Oscillators and Synthesizers, Poster Area<br>B3P-F: Sensors & Transducers, Poster Area<br>B3P-G: Microwave Freq Standards & Applications II, Poster Area<br>B3P-H: Timekeeping, Time & Freq Transfer, GNSS Apps II, Poster Area<br>B3P-J: Optical Frequency Standards & Applications II, Poster Area |
| 15:40 - 16:00 | Coffee / tea break |
| 16:00 - 17:40 | **Lecture Sessions B4**<br>B4L-A: Ion Clocks, Room P/X001<br>B4L-B: Timing Networks and Applications, Room P/L001<br>B4L-C: Atom Interferometers, Room P/L002 |
| 19:00 – 23.00 | **Conference Dinner** |

**<u>Thursday Apr 7th</u>**

| | |
|---|---|
| 08:00 - 18:00 | Registration |
| 08:40 - 10:20 | **Lecture Sessions C1**<br>C1L-A: Frequency Combs, Room P/X001<br>C1L-B: Caesium Frequency Standards, Room P/L001<br>C1L-C: Low Noise Synthesis, Room P/L002 |
| 10:20 - 10:50 | Coffee / tea break |
| 10:50 - 12:30 | **Lecture Sessions C2**<br>C2L-A: Lattice Clocks II, Room P/X001<br>C2L-B: CPT Cell Standards, Room P/L001<br>C2L-C: Opto-electronics and Microwave Oscillators, Room P/L002 |
| 12:30 - 14:00 | Lunch Break |
| 14:00 - 15:40 | **Lecture Sessions C3**<br>C3L-A: Optical Oscillators and Spectroscopy, Room P/X001<br>C3L-B: Optical Fibre Frequency Transfer, Room P/L001<br>C3L-C: Microwave Frequency Standards, Room P/L002 |
| 15.40 | Coffee / tea |
| 15:40 - | Lab Tours |

**<u>Friday Apr 8th</u>**

| | |
|---|---|
| 08:30-<br>16:00 | Satellite Workshop:<br>Optical clocks: quantum engineering and international timekeeping |

The Conference Laboratory will run in P/L006, Tuesday to Thursday from 09.00 – 17.00

# Useful Information

### Venue

The Exhibition Centre
University of York
Heslington, York
YO10 5NA, UK

Please ensure that you wear your badge at all times as admission to sessions, events, refreshments and lunches is by badge.

If you have any queries do not hesitate to ask any of the people manning the registration desk or wearing green badges

Tutorials on Monday 4th April will be held in P/L001 and P/L005 in the exhibition centre

If you wish to enter a session after it has started please enter via the back door if possible. In P/L001 and P/L002 the rear entrance is located at the top of the stairs in the corridor outside the lecture theatres. In P/X001 the rear door is located up the steps outside.

### Welcome reception and conference dinner

The welcome reception will be in the exhibition area from 6pm until 8pm on Monday. A selection of light refreshments will be provided.

The Conference Dinner is to be held in the National Railway Museum on Wednesday 6th April at 7.00 pm. Coach transport will be supplied from outside the Exhibition area at 6.30pm and will return between 10.30 and 11pm. Guests staying in hotels within the city centre will find that the NRM is a short walk from there. Initially follow signs for the station and then for the NRM. It will also be possible to travel on the supplied coaches to the Museum.

**Please note that the floor is uneven at the railway museum and therefore high heels are discouraged.**

### Emergency numbers

For any emergency dial 999, the call handler will ask which service you require. Alternatively dial 9999 from an internal phone. University security is 3333 and University emergency 4444.

### Registration and information desk

On Sunday the registration desk will be located in James college reception area from 17.00 to 19.00.

Monday – Thursday registration will be in the exhibition area and open from 08.00-18.00

### Internet Services

Complimentary WiFi will be available. There are two options to connect.

1. If you already have access to EDUROAM please select that network and if required give your normal user name and password.

2. Otherwise select CityConnectWiFi and follow the instructions. This network is also available in many places across York city centre.

## Food

All lunches will be held in the Galleria Restaurant next to the exhibition centre (exit near P/X001 and reception).

For evening meals, guests are free to make their own arrangements. There are two pubs which serve food in Heslington village: 'The Charles' is popular with the students, offering a range of value meal and drink deals; 'The Deramore Arms is more popular with mature students and academic staff, offering a good range of real ales and home cooked food.

For those guests who wish to venture into York, there is a wide range of establishments to choose from. Particular streets containing restaurants are: Walmgate, Fossgate, Goodramgate, Rougier Street, Micklegate and Lendal; but there are also many others. Many of the pubs serve food and most of the hotels also have their own restaurants. There are relatively few places to eat on the main shopping streets of Coney Street, Davygate and Parliament Street.

Breakfast for those staying in campus accommodation will be served in the Galleria restaurant, Roger Kirk Centre, on most days. Guests will be informed of any changes to the breakfast location when they collect their room keys.

## Camera and Filming Policy

Please refrain from taking any video or photographs during any of the conference sessions or poster presentations.

## Cell Phones and Alarms

As a courtesy to others please ensure that all phones and other alarms are turned off during all presentations.

## Smoking

All public buildings (including all the University buildings and the National Railway Museum are strictly **No Smoking**.

## Tipping and Taxes in the UK

Prices in restaurants do not always include a tip (or gratuity) but it should be stated on the menu if this is the case. If it is not included it is common to leave 10% to 15% for good service. VAT (20%) is included in the displayed price of any item for which it is charged.

## Bus stop and Sign posts

The best bus stop for the University is 'University Library' which is located under the first bridge that the bus passes after leaving the city centre or railway station. If you arrive by bus, the best signs to follow are those for the Physics and Electronics Departments which share the building with the exhibition centre but have better signage. The colleges are also relatively well signed from the bus stop. For Alcuin, walk up the steps around the corner from the bus stop. For Vanburgh and James, cross the road and join the walkway from the bridge.

# Presenter Information

## Session Chairs

Please ensure that you meet your presenters before the start of the session and that you know who is presenting each paper. Ensure the presentations have been loaded onto the computer. You will be provided with a timer and are expected to ensure that the session keeps to good time to allow people to switch between sessions with minimal disruption if necessary. Laser pointers will be provided. Please ensure that these are returned at the end of each presentation.

If a speaker is absent, please do not change the session schedule which may cause people to miss a presentation they had intended to listen to.

## Oral Presenters

The duration of a presentation slot is 20 minutes (40 minutes for invited speakers). You will have about 15 minutes for the presentation itself and about 5 minutes for questions from the audience (35 minutes for presentation and 5 minutes Q&A for invited speakers). Since most speakers spend an average of one minute per slide, it would probably be best if the number of slides in your presentation is around 15 (or 30-35 for invited speakers).

LCD projectors and computers (MS PowerPoint &Adobe Acrobat Reader) will be available in every session room for regular presentations. Overhead projectors, 35mm slides projectors and VHS videotape players are NOT available.

If you have special requests please let us know well in advance. An AV technician will be available should any assistance be needed.

All presentations must be pre-loaded in the talks upload area (close to the registration desk). Please do this the previous day (for those giving presentations on Tuesday this can be done during the welcome reception). Please bring a memory stick containing your presentation.

To avoid software compatibility problems (MS PowerPoint), speakers are advised to save their PowerPoint presentation in "pack-n-go" format AND bring a backup PDF version of their presentation. "Pack-n-go" format is used when burning a presentation to a CD for use on another computer that may or may not have your current version of PowerPoint installed. It installs a viewer capability. The file should be saved as "Package for CD" under the "File" tab in PowerPoint 2003, under the "File > Publish" tab in PowerPoint 2007, under “File > Save & Send > Package Presentation for CD” in PowerPoint 2010, and under “File > Export > Package Presentation for CD” in PowerPoint 2013.

# Poster Presentations

Poster boards will be available for presenters to put up their poster presentations. The size of each poster board is 100 cm (wide) by 250 cm (tall). Your poster will be attached using the fixings which will be provided.

The recommended format is **A0 portrait**: 84.1 cm x 118.9 cm (33.1 inch x 46.8 inch).

The location of your poster will be noted on each board in accordance with the corresponding number listed in the Programme Book given out at registration. You will be required to be present at your poster presentation during the hours listed in the Programme Book for the Poster Session, but your poster can remain in place all the time.

There will be a dedicated area for the student poster competition finalists in P/L005.

# Conference Lab

The conference lab (located in P/L006) provides hands-on experience in key areas of time and frequency metrology, including:

Frequency stability and phase noise of sources

Oscillator lab kits enabling modelling and measurement of the key parameters of oscillators

Inside a CPT atomic clock

Residual phase noise measurements of amplifiers and two-port devices

Operation of high performance test equipment with capability up to 7 GHz.

Test samples will be from major manufacturers.

Attendees are invited to bring their own devices, preferably with own connectors and power supply.

The lab will be open for the 3 conference days (9.00 – 17.00).

Staff will be available to assist at all times.

Contact persons: Wolfgang Schäfer (TimeTech) and Simon Bale (York)

# Opening and plenary session

The EFTF 2016 Scientific Committee is pleased to announce the following plenary session.

| | |
|---|---|
| Location | P/X001 |
| Date | Tuesday 5th April 2016 |
| Time | 8.40 - 10.40 |
| Chairs | Pascale Defraigne, Jeremy Everard and Ekkehard Peik |

**Professor Andrew Lyne**

Emeritus Professor of Physics, University of Manchester and former Director of the Jodrell Bank Observatory

'The formation, life and uses of pulsars - nature's finest cosmic clocks'

Pulsars are rapidly rotating neutron stars and are some of the most exotic objects in the universe. They are mostly only observable using radio telescopes. In this talk, I will provide an introduction to pulsars and how they are formed in the violence of the supernova collapse of large stars. I will describe how these massive cosmic flywheels can make superb clocks which can be used to conduct unique experiments in gravitation. In particular, they can be used to explore some of the fundamental laws of physics that determine how the universe evolved.

**David Rooney**

Curator of Time, Navigation and Transport at the Science Museum

'Selling time: Stories from the Greenwich Observatory'

What time is it? We are surrounded today by accurate time. We can hear time signals on the radio or look at automatically corrected kitchen clocks. Our home computers are synchronised by the internet or we can pick up the telephone and call the speaking clock. But how did people check the time before all this existed? In this lively illustrated talk, David Rooney tells the tale of how precise Greenwich time has increasingly been distributed around Britain, Europe and the world from humble local beginnings in the early nineteenth century. It includes stories of scientists and telephonists, terrorists and horologists, poets and paupers, bombers and bell-ringers, from millionaires and murderers to the Greenwich Time Lady and the Girl with the Golden Voice. Rooney reveals the human faces behind the remorseless tick of the clock.

# EFTF 2016 Awards

Two awards, sponsored by the UK National Physical Laboratory, will be presented at EFTF 2016 to recipients selected by the Executive Committee of the EFTF.

## European Frequency and Time Award 2016

### Harald Schnatz

"for his seminal contributions to different but interrelated fields of most accurate time and frequency measurements and dissemination in particular the first phase coherent measurement of a frequency standard in the visible and the dissemination of stable and accurate frequencies via optical fibre networks"

## EFTF Young Scientist Award 2016

### Nils Huntemann

"for the development and evaluation of an optical clock based on the octupole transition in a single $^{171}Yb^{+}$ ion with an uncertainty at the $10^{-18}$ level"

# Sponsors of the student travel support programme

The EFTF 2016 Organising committee gratefully acknowledges the support of the following companies and institutions.

CSEM Centre Suisse d'Electronique et de Microtechnique

First-TF

FSRM

Fondation Suisse pour la recherche en microtechnique

Helmholtz Fonds e.V.

Meinberg Funkuhren

Morion

Société Française des Microtechniques et de Chronométrie (SFMC)

Spectratime

T4Science

TimeTech

TOPTICA Photonics AG

Université de Neuchâtel

# Student Finalists

The following papers were selected as finalists by the EFTF 2016 Scientific Committee for the Student Poster Competition. This year, the student poster awards are sponsored by the UK National Physical Laboratory.

| | |
|---|---|
| Date and Time | Tuesday 5th April, 14.00 – 15.40 |
| Location | P/L005<br>Posters will remain up for the whole conference<br><br>Papers marked with an L are also being given as lectures |

| Paper ID | Group | Title |
|---|---|---|
| (L) #1061# | 1 & 4 | Elimination of Spurious Modes in Zinc Oxide Resonators<br>***Ossama Mortada***, *Matthieu Chatras, Abedelhalim Zahr, Pierre Blondy, Aurelian Crunteanu,Jean Christophe Orlianges* |
| (P) #1109# | 1 & 4 | Mapping Acoustic Field Distributions of VHF to SHF SAW Transducers Using a Scanning Electron Microscope<br>***Aurelien Godet***, *Jean-Michel Friedt, Sounkalo Dembele, Nadine Piat, Abdelkrim Khelif, Pascal Vairac, Joel Agnus, Pierre Yves Bourgeois, Gwenhael Goavec-Merou* |
| (L) #1125# | 1 & 4 | S0 Lamb Wave Resonators for in-Liquid Sensing: Promising Alternative to Shear Bulk Acoustic Wave Devices<br>***Teona Mirea***, *Ventsislav Yantchev, Enrique Iborra* |
| (P) #1206# | 1 & 4 | Build-Up Detection and Level Monitoring by Using Capacitive Glocal Technique<br>***Fovad Ali Khan***, *Adnan Yousaf* |
| (L) #1043# | 2 | Frequency Synthesis from Cryogenic Sapphire Oscillator<br>***Etienne Vaillant***, *Fabrice Sthal, Joël Imbaud, Christophe Fluhr, Serge Grop, Vincent Giordano, Enrico Rubiola, François-Xavier Esnault, Gilles Cibiel* |
| (P) #1177# | 2 | Digital Electronics Based on Red Pitaya Platform for Coherent Fiber Links<br>***Andrea Carolina Cardenas Olaya***, *Cecilia Clivati, Alberto Mura, Matteo Frittelli, Enrico Rubiola, Jean-Michel Friedt, Claudio Eligio Calosso* |
| (P) #1227# | 2 | Optical to Microwave Synchronization with Sub-Femtosecond Daily Drift<br>***Aram Kalaydzhyan***, *Michael Peng, Franz Kaertner* |
| (L) #1234# | 2 | Low Phase Noise 10MHz Crystal Oscillators<br>***Tsvetan Burtichelov***, *Jeremy Everard* |
| (L) #1235# | 2 | Brillouin Scattering in a Lithium Fluoride Crystalline Resonator for Microwave Generation<br>***Souleymane Diallo***, *Guoping Lin, Jean Pierre Aubry, Yanne Yanne* |
| | | |

| | | |
|---|---|---|
| (L) #1048# | 3 | A High-Performance CPT-Based Cs Vapor Cell Atomic Clock Using Push-Pull Optical Pumping<br>***Moustafa Abdel Hafiz****, Rodolphe Boudot* |
| (P) #1099# | 3 | Light Shifts Studies in CW and Ramsey Double Resonance Vapor Cell Frequency Standards<br>***Mohammadreza Gharavipour****, Ivan S Radojičić, Florian Gruet, Christoph Affolderbach, Aleksandar J Krmpot, Brana M Jelenkovi, Gaetano Mileti* |
| (P) #1112# | 3 | Non-Destructive MEMS Atomic Vapor Cells Characterization by Raman Spectroscopy and Image Analysis<br>***Sylvain Karlen****, Jean Gobet, Thomas Overstolz, Jacques Haesler* |
| (L) #1139# | 3 | Progress on the CPT Clock: Reduction of the Main Frequency Noise Sources<br>***Francois Tricot****, Sinda Mejri, Peter Yun, Bruno Francois, Jean-Marie Danet, Stephane Guerandel, Emeric De Clercq* |
| (L) #1156# | 3 | Toward Self Spin-Squeezing in a BEC Atom Clock<br>***Theo Laudat*** |
| (P) #1008# | 5 | Using Known Ground Station Clock Offsets to Improve Tropospheric Delay Estimates at NIMT Timing Station<br>***Chaiyaporn Kitpracha****, Thayathip Thongtan, Pornchanit Moonaksorn, Rata Suwantong, Chalermchon Satirapod* |
| (P) #1057# | 5 | Multi-Clock Dissemination via One Ring-Like Fiber Network<br>***Wei Chen****, Qin Liu, Jialiang Wang, Nan Cheng, Youzhen Gui, Haiwen Cai* |
| (P) #1089# | 5 | Time Transfer Over a White Rabbit Network<br>***Namneet Kaur****, Paul-Eric Pottie, Philip Tuckey* |
| (P) #1095# | 5 | Synchronous Mode-Locked Laser Network with Few-Fs Jitter and Multi-km Distance<br>***Kemal Shafak****, Ming Xin, Michael Y Peng, Franz X Kaertner* |
| (P) #1208# | 5 | Optimized 1f-2f Actively Compensated Frequency Synchronization<br>***Xi Zhu****, Bo Wang, Chao Gao, Yibo Yuan, Jingwen Dong, Lijun Wang* |
| (L) #1027# | 6 | Quantum Logic State Detection for Molecular Ions<br>***Fabian Wolf****, Yong Wan, Jan Heip, Florian Gebert, Chunyan Shi, Piet Schmidt* |
| (L) #1070# | 6 | Carrier-Envelope Offset Characterization in a Semiconductor Modelocked Laser Without f-to-2f Interferometry<br>***Pierre Brochard****, Nayara Jornod, Valentin Wittwer, Stéphane Schilt, Dominik Waldburger, Sandro Link, Cesare Alfieri, Matthias Golling, Laurent Devenoges, Jacques Morel, Ursula Keller, Thomas Südmeyer* |
| (L) #1158# | 6 | Atomic Quadrupole Moment Measurement Using Dynamic Decoupling<br>***Ravid Shaniv*** *, Nitzan Akerman, Roee Ozeri* |

| | | |
|---|---|---|
| (L) #1163# | 6 | 87Sr and 88Sr Optical Lattice Clocks at NPL<br>*Ian Hill, Richard Hobson, **William Bowden**, Marco Menchetti, Antoine Rolland, Fred Baynes, Helen Margolis, Patrick Baird, Kai Bongs, Patrick Gill* |
| (L) #1171# | 6 | State-of-the-Art Ultra-Low Phase Noise Photonic Microwave Generation and Characterization<br>***Romain Bouchand**, Xiaopeng Xie, Daniele Nicolodi, Pierre-Alain Tremblin, Giorgio Santarelli, Christophe Alexandre, Michele Giunta, Matthias Lezius, Wolfgang Haensel, Ronald Holzwarth, Datta Shubhashish, Joshi Abhay, Yann Le Coq* |

# Local Organising Committee

| | |
|---|---|
| Jeremy Everard (Chair) | University of York |
| Simon Bale | University of York |
| Tsvetan Burtichelov | University of York |
| Linda Dawson | University of York |
| Matthew Kilburn | University of York |
| Helen Margolis (vice-chair) | National Physical Laboratory |
| Sundeep Bhandari | National Physical Laboratory |
| Patrick Gill | National Physical Laboratory |
| Rachel Godun | National Physical Laboratory |
| Leon Lobo | National Physical Laboratory |
| Krzysztof Szymaniec | National Physical Laboratory |
| Peter Whibberley | National Physical Laboratory |
| Mike Underhill | Underhill Research |
| Joël Petetin | Observatoire de Besançon |

# EFTF 2016 Executive Committee

Elected Members

- Ekkehard Peik - Physikalisch-Technische Bundesanstalt, Germany (Chair)
- Gaetano Mileti - Laboratoire Temps-Frequence, Switzerland (Tutorial Chair)
- Wolfgang Schaefer - TimeTech, Germany (Exhibition Chair)
- Patrizia Tavella - Istituto Nazionale di Ricerca Metrologica, Italy (Vice Chair)
- François Vernotte - Université de Franche-Comté, France (Academic Chair)
- Pierre Waller - European Space Agency, The Netherlands (Awards Chair)
- Bernard Dulmet - ENSMM, France
- Jeremy Everard - University of York, United Kingdom
- Helen Margolis - National Physical Laboratory, United Kingdom
- Pascal Rochat - Spectratime SA, Switzerland

Ex Officio Members

- Sébastien Thibaud - SFMC, France
- Pascale Defraigne - Royal Observatory of Belgium (Scientific Committee Chair)
- Michael Driscoll - Northrop Grumman Electronic Systems, USA (IEEE-IFCS Standing Committee Chair)
- Luke Maleki - OEwaves, USA (EFTF/IFCS 2017 Co-General Chair)

# EFTF 2016 Scientific Committee

**Chair: Pascale Defraigne** - Royal Observatory of Belgium

***Group 1: Materials, Resonators, & Resonator Circuits***

**Alexandre Reinhardt - CEA-LETI, France (Vice chair)**
Thomas Baron - FEMTO-ST, France
Emmanuel Defay - Luxembourg Institute of Science and Technology, Luxembourg
Marc Faucher - IEMN, France
Songbin Gong - University of Illinois at Urbana-Champaign, USA
Olivier Le Traon - ONERA, France
Matteo Rinaldi - Northeastern University, USA
Ashwin Seshia - University of Cambridge, UK
Dana Weinstein - MIT, USA
Ventsislav Yantchev - Uppsala University, Sweden

***Group 2: Oscillators, Synthesizers, Noise, & Circuit Techniques***

**Jean-Pierre Aubry - Aubry Conseil, Switzerland (vice chair)**
Claudio Calosso - INRIM, Italy
Gilles Cibiel - CNES, France
Jeremy Everard - York University, UK
David Howe - NIST, USA
Olivier Lopis - LAAS, France
Enrico Rubiola - Femto-ST, France
Fabrice Sthal - Femto-ST, France
Michael Tobar - University Western Australia, Australia
Mike Underhill - Underhill Research, UK

***Group 3: Microwave Frequency Standards***

**Stefan Weyers - PTB, Germany (Vice chair)**
Marco Belloni - ESA, Italy
Kurt Gibble - Penn State University, USA
John Kitching - NIST, USA
Motohiro Kumagai - NICT, Japan
Arnaud Landragin - SYRTE, France
Salvatore Micalizio - INRIM, Italy
Gaetano Mileti - Universite de Neuchatel, Switzerland
Krzysztof Szymaniec - NPL, UK
Qinghua Wang - Spectratime, Switzerland

***Group 4: Sensors & Transducers***

**Svenja Knappe - NIST, USA (Vice chair)**
Ventsislav Yantchev - Uppsala Observatory, Sweden
Sylvain Ballandras - Frecnsys, France
Ralf Lucklum - University of Magdeburg, Germany
Paul Muralt - EPFL, Switserland
Leonhad Reindl - Uni Freibourg, Germany
Victor Plessky - GVR Trade SA, Switzerland
Holger Fritze - TU Clausthal, Germany
Diethelm Johannsmann - TU Clausthal, Germany
Alfred Binder - CTR AG, Austria

***Group 5: Timekeeping, T&F Transfer, Telecom and GNSS applications***
**Pierre Waller - ESA-ESTEC, The Netherlands (Vice chair)**
Anne Amy-Klein - LPL (CNRS, UP13), France
Andreas Bauch - PTB, Germany
Laurent-Guy Bernier - METAS, Switzerland
Jerome Delporte - CNES, France
Miho Fujieda - NICT, Japan
Gesine Grosche - PTB, Germany
Per Olof Hedekvist - SP, Sweden
Judah Levine - NIST, US
Huang-Tien Lin - NTFSL - TL, Taiwan
Xiao Chun Lu - NTSC, China
Nathan Newbury - NIST, US
Vitaly Pal'chikov - VNIIFTR, Russia
Ed Powers - USNO, US
Maria Ramos - ESA-ESOC, Germany
Wolfgang Schaefer - TimeTech, Germany
Amitava Sen Gupta - NPLI, India
Patrizia Tavella - INRIM, Italy
Philip Tuckey - LNE-SYRTE OP, France
Pierre Uhrich - LNE-SYRTE OP, France
Hongbo Wang - BIRM, China
Peter Whibberley - NPL, UK
Michael Wouters - NMI, Australia
Aimin Zhang - NIM, China
Victor Zhang - NIST, US

***Group 6: Optical Frequency Standards and Applications***
**Helen Margolis - NPL, UK (Vice chair)**
Luigi Cacciapuoti - ESA, The Netherlands
Davide Calonico - INRIM, Italy
Roman Ciuryło - Nicolaus Copernicus University, Poland
Pierre Dubé - NRC, Canada
Patrick Gill - NPL, UK
Kazumoto Hosaka - AIST/NMIJ, Japan
Tetsuya Ido - NICT, Japan
Steve Lecomte - CSEM, Switzerland
Yann Le Coq - LNE-SYRTE, France
Christian Lisdat - PTB, Germany
Jérôme Lodewyck - LNE-SYRTE, France
Andrew Ludlow - NIST, USA
Andre Luiten - University of Adelaide, Australia
Long-Sheng Ma - East China Normal University, China
Mikko Merimaa - MIKES Metrology, VTT Technical Research Centre of Finland Ltd,
Jacques Morel - METAS, Switzerland
Ekkehard Peik - PTB, Germany
Thomas Südmeyer - LTF-UNINE, Switzerland
Alexey Taichenachev - Institute of Laser Physics, Russia

# Social Programme

**Monday 4th April** **Welcome reception in exhibition centre**

**18:00 – 20:00**

Join us for a welcome drink and a selection of light food.

**Wednesday 6th April** **Conference Dinner at the National Railway Museum**

**18:30** Coach

**19:00 – 23:00** Reception and dinner

Take this opportunity to visit this fascinating museum with its large range of engines and railway coaches. Coaches will depart from outside the exhibition centre at 18.30 and will return between 22.30 and 23.00. EFTF and Student awards will be presented during the dinner.

**Thursday 7th April,** **Lab Tours**

**15:40 onwards**

If you are interested in visiting some of the laboratories within the Department of Electronics, University of York, please sign up for the tours which will take place after the conference has ended. Sign-up sheets will be located at the reception desk.

# Coach Tours

**Wednesday 6th April** **Day trip to Fountains Abbey world heritage site**

**09:30 - ~16:30**

A coach will leave the exhibition centre at about 09.30 and will return at about 16.30. This visit is intended primarily for the partners of conference attendees. The coach is provided free of charge but guests are expected to pay for their own admittance.

**Thursday 7th April** **Day trip to Castle Howard**

**09:30 - ~16:30**

A coach will leave the exhibition centre at about 09.30 and will return at about 16.30. This visit is intended primarily for the partners of conference attendees. The coach is provided free of charge but guests are expected to pay for their own admittance.

# Tutorial schedule: Monday 4th April

| | Tutorials - Track 1 (Room: P/L001) | Tutorials - Track 2 (Room: P/L005) |
|---|---|---|
| 08:30 - 10:00 | **K Szymaniec, NPL** '*Cs Primary frequency standards*' | **P Tavella, INRIM** '*Precise Time Scales and Navigation Systems, the Ultimate Challenge to Time Metrology*' |
| 10:00 | Coffee / tea break | |
| 10:15 - 11:45 | **S Micalizio, INRIM** '*Vapor cell frequency standards*' | **P Defraigne, ROB** '*Global Navigation Satellite Systems*' |
| 11:45 | Lunch break | |
| 13:00 - 14:30 | **E Peik, PTB** '*Optical clocks*' | **C Nelson, NIST** *'Phase noise measurements'* |
| 14:30 | Coffee / tea break | |
| 14:45 - 16:15 | **S Webster, M2L** '*Lasers for optical frequency standards*' | **E Rubiola, FEMTO-ST** '*Phase noise and jitter in digital electronics*' |
| 16:15 | Coffee / tea break | |
| 16:30 - 18:00 | **G Grosche, PTB** *'Frequency and time transfer using optical fibers'* | **B Neubig, AXTAL** '*Measurement techniques for piezoelectric resonators*' |

**Welcome Reception 18.00 – 20.00 Exhibition Centre**

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**Krzysztof Szymaniec - *Cs Primary frequency standard***

In 2015, the metrology community celebrated 60 years of the atomic clock. Seminal works of Rabi, Ramsey, Essen and others initiated a disruptive change in timekeeping and led to a new definition of the second based on atomic rather than astronomical phenomena. Decades of subsequent development improved the accuracy of atomic clocks and frequency standards by orders of magnitude with measurement uncertainties currently left at the sixteenth decimal place. In particular, the introduction of laser cooling and construction of atomic fountains have boosted these improvements. Nowadays, more than two decades after its first demonstration, fountain technology appears quite mature and calibrations of the global timescale TAI/UTC rely almost entirely on the fountain standards. In addition, atomic fountains are often used to discipline clocks forming local timescales. A cold atom clock similar to a fountain, but designed to operate in a microgravity environment, will soon be launched and installed on board of the International Space Station for stringent tests of general relativity. On the ground, atomic fountains give important input into the search for a possible time variation of fundamental constants of nature. These devices are also invaluable tools in the development of optical clocks, the anticipated next generation of primary frequency standards.

In this tutorial, I will begin with presenting the basic principle of an atomic clock and a description of a generic atomic fountain set-up. The focus of the lecture will then be on discussing the noise effects limiting short-term stability and systematic effects affecting the accuracy of atomic fountain clocks. The presentation will be given from a 'practitioner' point of view and will conclude with discussing applications of the fountain standards and prospects for further development.

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**Salvatore Micalizio - *Vapor cell frequency standards***

Since their first realization in the 1960s, vapour-cell frequency standards have been considered extremely attractive devices in all those applications where good frequency stability performances joined with small sizes, reliability, reduced power consumption and costs are required. These applications include telecommunication, defence, energy, space and radio-navigation. The passive rubidium frequency standard with state selection performed by the incoherent light of a lamp is still nowadays widely adopted in many measurement systems, as well as in advanced technological sectors, such as GPS and GALILEO.

The development of single mode semiconductor laser diodes in the 1980s opened new perspectives in the field of gas cell frequency standards, thanks to the replacement of the discharge lamp with a coherent optical source. In terms of frequency stability, the expected performance improvement was theoretically estimated to be 2-3 orders of magnitude, predicting a white frequency noise limit in the $10^{-14}\,\tau^{-1/2}$ region, $\tau$ being the integration time. However, laser noise transferred to the clock signal via the light-shift effect prevented this result from being reached. In the last twenty years, innovative schemes have been considered with the aim of approaching the expected theoretical limit and new concept laser-pumped frequency standards have been developed. These clocks are the object of this tutorial.

After resuming the main features of the traditional lamp-pumped Rb clock, the tutorial will focus on several interesting approaches that have been envisaged not only to get close to the fundamental stability limit, but also to reduce at the same time the requirements on the laser noise. These techniques include coherent population trapping, light-shift compensated schemes and pulsed optical pumping. The tutorial will describe these proposals, their main advantages and limitations and the most significant results obtained by various research groups.

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**Ekkehard Peik -** ***Optical clocks***

Optical clocks based on laser cooled and trapped atoms (in optical lattices at the 'magic' wavelength) and ions (in radiofrequency Paul traps) have made fast progress in recent years, with the most advanced systems now reaching an instability of $10^{-16}$ in only 10 s of averaging time and a systematic uncertainty in the low $10^{-18}$ range. This lecture will discuss the principles, experimental requirements and methods that have enabled these performances. Emphasis will be placed on the different atomic systems and types of 'forbidden' reference transitions, and on the spectroscopic methods that provide the required control of systematic frequency shifts, especially those associated with the interaction with external electric and magnetic fields. I will also discuss the conceivable future directions for the reliable evaluation and for scientific applications of atomic frequency standards with an uncertainty below that of Cs clocks.

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**Stephen Webster -** ***Lasers for optical frequency standards***

Over the past 50 years, atomic clocks have been based on microwave frequencies and primary standards have demonstrated uncertainties at the level of a few parts in $10^{16}$. Optical clocks are a new generation of atomic clock, in which the frequency of light is the signal used for timing. They are based on 'forbidden' atomic transitions for which light is absorbed over a very narrow range of frequencies. Depending on the particular atomic species and transition used, the ratio of the frequency to the frequency width (Q-factor) ranges from $10^{14}$-$10^{23}$, thus, these transitions constitute very precise frequency references. They are also insensitive to external electromagnetic fields and can be highly reproducible with uncertainties at the level of parts in $10^{18}$. Further, given that the frequency of light is ~100,000 times higher than that of microwaves, the same level of precision as a microwave atomic clock may be reached in a much shorter time. As optical clocks come of age and prove the stability and reproducibility predicted of them, the prospect will open up for a redefinition of the second in terms of an optical frequency.

The atomic absorber in an optical clock takes one of two forms: it is either a single ion confined in an electro-dynamic trap (Paul trap), or an ensemble of neutral atoms held in an electric dipole force trap (optical lattice). The atomic absorbers are laser cooled so that they are nearly at rest and, to first order, do not experience a Doppler shift on interaction with the light used to probe the atomic transition. To make use of the high-Q of the atomic transition, the probe light must also have a very narrow frequency width and this is achieved by stabilizing a laser to a secondary reference, a high-finesse Fabry-Pérot etalon. A mode-locked femtosecond-pulsed laser (femtosecond comb) converts the very rapid oscillations of the light from some 100s of THz down to a radio frequency so that the output of the optical clock can be counted by commercial electronics and compared to the SI second and the outputs of other optical clocks.

This tutorial will give an overview of the essential elements of an optical clock: the atomic reference, the ultra-stable laser and the femtosecond comb. It will describe how each of these elements is realized in practice and the experimental challenges involved in operating such an apparatus. In particular, a review will be made of the laser sources required for operation of an optical frequency standard, the techniques employed in their stabilisation and the characterization of their noise.

**Gesine Grosche - *Frequency and time transfer using optical fibers***

Ever more accurate clocks and frequency references are being developed in dedicated laboratories around the world, reaching astonishingly low instability and high accuracy, currently near 1 part in10 to the 18. Making the ultra-stable output of these powerful instruments available beyond the walls of the metrology laboratory, to enable physics experiments, remains a challenge. In the wake of the optical telecommunication revolution, transfer techniques that make use of optical fibre have greatly developed: within one decade, improvements of more than three orders of magnitude in precision have been achieved.

Recently, long-distance frequency transfer with an uncertainty of 2 parts in 10 to the 20, and, for 1 km-scale links, synchronisation at the level of femto-seconds has been reported. Fibre based transfer of frequency has been achieved over distances exceeding 1000 km, which enables international comparisons of clocks and other joint experiments.

In this tutorial I will illustrate advantages and challenges of using optical fibre as a transmission medium for precision metrology. This will cover basic concepts, techniques and limitations, focussing on optical telecommunication fibre (1.55 µm), which is both cheap and optimised for low loss, making it suitable for long-distance transfer. The tutorial will give an overview and comparison of different transfer techniques centred on methods using the optical carrier phase.

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**Patrizia Tavella - *Precise Time Scales and Navigation Systems, the Ultimate Challenge to Time Metrology***

Today, atomic clocks enable precision estimates of time and position. Through the use of ultra-precise atomic frequency standards, we can form time scales, such as the international time standard Universal Coordinated Time (UTC), capable of dating events with nanosecond accuracy. Similarly, Global Navigation Satellite Systems (GNSS), provide location all over the world with sub-meter accuracy.

In timekeeping, as well as in navigation systems, the questions may be similar, but the answers are frequently dissimilar, due to different goals, requirements, technology availability and constraints. In both cases precision clocks, measuring systems, and a reference time scale are required; in both cases we need to estimate how often the clocks are to be resynchronized and what is the acceptable time error that a clock may accumulate without compromising system performance. We require a mathematical model to predict clock behaviour in order to maintain agreement with another reference clock or to ensure updated navigation messages. We need to understand the 'normal' behaviour of a clock to be able to quickly identify anomalies which can lead to incorrect estimates.

This lecture presents the needs of precise Timing and Navigation, explaining the current international timekeeping architectures and the timing systems of the current GNSS, giving insight to the most demanding topics that still challenge Time Metrology.

**Pascale Defraigne -** ***Global Navigation Satellite Systems***

GNSS and Time have a bi-directional relationship. On the one hand, GNSS also relies on time: everything is based on the measurements of the signal travel time between the satellite and the receiver. GNSS therefore needs a reference timescale maintained by the operators and broadcast by the satellites. On the other hand, the satellite navigation systems offer a wonderful tool for time and frequency metrology, as these flying atomic clocks on board the satellites can be used as a reference for the comparison of ground time and frequency standards.

This tutorial will raise both aspects of the link between GNSS and TIME. After showing concretely the need for accurate time scales for the GNSS, the 'GNSS time transfer' technique will be detailed. Code and carrier phase measurements will be presented and the procedure to get a precise and accurate clock comparison will be explained, both from the instrumental point of view and in terms of data analysis. GNSS Common View (or All in View) as well as Precise Point Positioning will be detailed in the presentation. The different error sources on the measurements will be studied and hence an ideal station set-up will be presented.

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**Craig Nelson -** ***Phase noise measurements***

Noise is everywhere. Its ubiquitous nature interferes with or masks desired signals and fundamentally limits all electronic measurements. Noise in the presence of a carrier is experienced as amplitude and phase modulation noise. Modulation noise will be covered from its theory, to its origins and consequences. The effects of signal manipulation such as amplification, frequency translation and multiplication on spectral purity will be examined. Practical techniques for measuring AM and PM noise, from the simple to complex will be discussed. Typical measurement problems, including the cross-spectrum anti-correlation, will also be covered.

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**Enrico Rubiola -** ***Phase noise and jitter in digital electronics***

Digital electronics is progressively replacing analog electronics, even in applications where low noise is critical. When the analog signal cannot be avoided, the world is still going digital, with analog-to-digital and digital-to-analog conversion as the natural complement. The reasons are obvious: simplicity, reproducibility, cost, and no or minimal calibration. Additionally, youngsters are trained to digital, not to analog, and the digital hardware benefits from the Moore law.

Having said that, we go through phase noise in digital electronics and in the analog-digital interface, focusing on frequency applications, synthesis, and measurement. This tutorial will cover the following topics, deriving most of the concepts from examples.

- Review of definitions and principles. Phase noise spectrum, Allan deviation, jitter, quantization noise, and aliasing.
- Simplified model of a digital circuit. Front-end, sin-to-square conversion, aliasing, and clock distribution. The Egan model for frequency synthesis.

- Basic noise types found in digital electronics. Phi-type noise (regular and aliased), X-type noise (regular and aliased), chattering (multi-bouncing), and thermal effects.
- The volume law, which states the unfortunate fact that big cell size is better.
- On-chip PLL and clock frequency multiplication.
- Noise in digital chips. Model, examples, and analysis of a few phase noise spectra (FPGA, SoC, CPLD, TTL). VHF and microwave digital dividers. The classical Π (regular) scheme and the de-aliased Λ scheme.
- Direct Digital Synthesizer (DDS). Principles. Noise from truncation and non-linearity. Examples, and analysis of a few phase noise spectra.
- Phase noise in analog-to-digital converters.

This is a new tutorial, mostly based on material not available in the general literature. The author owes gratitude to P. Y. Bourgeois, C. E. Calosso, J. M. Friedt, G. Goavec-Merou, Y. Gruson, and the Go Digital Working Group at the FEMTO-ST Institute.

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**Bernd Neubig -** ***Measurement techniques for piezoelectric resonators***

This tutorial covers the measurement techniques for piezoelectric resonators in a wide frequency range, from low-frequency (tuning fork) resonators in the kHz range, over AT- and SC-cut resonators in the MHz range to HFF and SAW resonators up to the GHz range. Special emphasis will be given to the relevant IEC standards.

In this tutorial, I will discuss the following measurement techniques with their pros and cons:

- Classical Zero-Phase measurement technique (IEC 60444-1 and 60444-2)
- Measurement of resonator parameters up to >1 GHz by using modern network analysers with error correction (IEC 60444-5, EIA-512)
- Direct measurement of load resonance (IEC 60444-4 and 60444-11)
- Test fixtures for THD and SMD resonators (IEC 60444-1, 60444-5 and 60444-8)
- Measurement on low-frequency resonators (kHz) (IEC 60689)
- Drive Level Dependency (DLD) measurement to identify irregular non-linear resonator behaviour (IEC 60444-6 Ed 2)
- Characterization of activity dips and frequency jumps occurring over a narrow temperature interval (IEC 60444-7)
- Measurement of spurious resonances and their parameters (IEC 60444-9)
- Determination of frequency aging (IEC 60122-1, MIL-PRF-3098)

# Detailed Conference Programme

## Tuesday 5th April

| | | | |
|---|---|---|---|
| | **P/X001**<br>**Opening session and plenary lectures** | | |
| 8.40-<br>10.40 | **Professor Andrew Lyne**<br>The formation, life and uses of pulsars - nature's finest cosmic clocks<br><br>**David Rooney**<br>Selling time: Stories from the Greenwich Observatory<br><br>Chairs: Pascale Defraigne, Jeremy Everard and Ekkehard Peik | | |
| 10:40 | Coffee/tea break | | |
| | **Lecture sessions** | | |
| | **P/X001** | **P/L001** | **P/L002** |
| 11:10-<br>12.30 | A1L-A<br><br>**Timescales and SI Second**<br><br>Chr: Victor Zhang<br><br>Track: Timekeeping, Time and Frequency Transfer, GNSS Applications | A1L-B<br><br>**Cold Atoms for Sensors and Clocks**<br><br>Chr: Franck Pereira dos Santos<br><br>Track: Microwave Frequency Standards | A1L-C<br><br>**Piezoelectric Resonators I**<br><br>Chr: Alexandre Reinhardt<br><br>Track: Materials, Resonators, & Resonator Circuits |
| 12.30 | Lunch | | |
| 14.00-<br>15.40 | Poster session 1 Exhibition Centre, Student poster finalists P/L005 | | |
| 15.40 | Coffee / tea break | | |
| 16:00-<br>17:40 | A3L-A<br><br>**Lattice Clocks I**<br><br>Chr: Ekkehard Peik<br><br>Track: Optical Frequency Standards and Applications | A3L-B<br><br>**Space Applications**<br><br>Chr: Marco Belloni<br><br>Track: Timekeeping, Time and Frequency Transfer, GNSS Applications | A3L-C<br><br>**Sensors**<br><br>Chr: Svenja Knappe<br><br>Track: Sensors & Transducers |

**A1L-A Timescales and SI Second P/X001**
**Chair Victor Zhang**

**11:10 Towards Redefining the SI in 2018 (Invited) #1019#**

Luc Erard
LNE, France

During its 25th session held in November 2014 in Versailles, The General Conference on Weights and Measures (CGPM) re-confirmed its intention to adopt new definition for the the following base units: the kilogram, the ampere, the kelvin and the mole, leaving the present definition of the second, meter and candela unchanged. The new definition of the units should be based on fixed numerical values of fundamental constants respectively: the Planck constant h, the elementary charge e, the Boltzmann constant k and the Avogadro constant NA. The new definitions are chosen to maintain continuity, so that the magnitude of the four redefined units in the “new SI” will be essentially identical to their magnitude at the moment of adoption. The limits of the present system will be presented first, then the choice that have been made to arrive at these proposals, and further details of the change involved in the “new SI”.

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**11:50 National Time Scale and Primary Frequency Standard of VNIIFTRI: Current Status #1230#**

Sergey Golubev{2}, Sergey Donchenko{1}, Igor Blinov{1}, Vitaly Palchikov{1}, Aleksander Goncharov{1}, Leilya Gerieva{2}
{1}FGUP VNIIFTRI, Russia; {2}Rosstandart, Russia

The national time scale of the Russian Federation is reproduced and maintained based on the State standard of time and frequency operated at a facility located in Mendeleevo, Moscow Region. The aim of the VNIIFTRI system of primary frequency standards, comprising two caesium fountains, is to perform regular calibrations of the international time-scale TAI/UTC at the highest accuracy and to provide a stable reference for the construction and steering of UTC(SU), the local representation of UTC in Russia.

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**12:10 Incorporating Optical Clocks Into UTC(k) Time-Scales #1159#**

Peter Whibberley, Helen Margolis, Patrick Gill
NPL, United Kingdom

Improvements in the performance of optical clocks have led to increasing interest in their use for steering UTC(k) time-scales. During the ITOC campaign of European optical clock comparisons in June 2015, the NPL Sr lattice and Yb+ ion trap clocks were measured against the H-maser generating UTC(NPL) over 26 days, with availabilities in excess of 70%. We have used the data to simulate steering UTC(NPL) to one or both of the optical clocks, investigated strategies for dealing with the dead times, and compared the results with the BIPM Circular T.

| A1L-B | Cold Atoms for Sensors and Clocks | P/L001 |
|---|---|---|
| Chair | Franck Pereira dos Santos | |

**11:10 Towards Self Spin-Squeezing in a BEC Atomic Clock #1156#**

Theo Laudat{1}, Vincent Dugrain{2}, Jakob Reichel{2}, Peter Rosenbusch{1}
{1}Observatoire de Paris - SYRTE, France; {2}UPMC, France

State-of-the-art microwave-frequency standards have reached the quantum projection noise limit, and using spin-squeezing is an appealing approach to overcome this fundamental boundary. Spin squeezed states are quite hard to produce in the case of 87Rb spinor condensate as they require to greatly modify the interstate atomic interaction g↑↓". We present a new method where the system reduces g↑↓" by itself without user intervention, leading to spontaneous spin squeezing in a BEC clock.

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**11:30 The Matter-Wave Laser Interferometric Gravitation Antenna (MIGA) Project: New Perspectives for High Precision Gravity Measurements #1093#**

Arnaud Landragin
CNRS-Observatoire de Paris-UPMC, France

The Matter-wave laser Interferometric Gravitation Antenna (MIGA) project aims at demonstrating precision measurements of gravity with cold atom sensors in a large scale underground instrument and at studying the associated powerful applications in geosciences and fundamental physics

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**11:50 Atomic Sources for Gravitational Wave Detectors #1130#**

Christian Schubert, Sven Abend, Holger Ahlers, Wolfgang Ertmer, Naceur Gaaloul, Sina Loriani, Dennis Schlippert, Ernst Rasel
Institut für Quantenoptik, Leibniz Universität Hannover, Germany

Gravitational wave detectors based on atom interferometry were proposed in earth bound setups and space borne configurations. The latter may feature a baseline exceeding few kilometres and consequently require an atomic species with an optical clock transition to suppress laser frequency noise. This contribution will present a trade-off for several atomic species considering the flux, residual expansion rates and other parameters affecting the performance.

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**12:10 Diffractive Optics for a Compact, Cold-Atom Microwave Clock #1127#**

James Patrick McGilligan, Rachel Elvin, Paul F. Griffin, Erling Riis, Aidan S. Arnold
University of Strathclyde, United Kingdom

Laser cooled atomic samples have resulted in profound advances in frequency metrology, however the technology is typically complex and bulky. In recent literature [1] we describe a micro-fabricated optical element that greatly facilitates miniaturisation of ultra-cold atom technology. Portable devices should be feasible with accuracy vastly exceeding that of equivalent room-temperature technology, with a minimal footprint. These laser cooled samples are ideal for atomic clocks. Here we will discuss next generation diffractive optical elements (DOE) that have been optimised for implementation in cold atom apparatus. Furthermore, we will demonstrate our work towards building a robust, compact cold atom clock based on a Raman-Ramsey interrogation of the cold atomic sample.

**A1L-C Piezoelectric Resonators I P/L002**

**Chair Alexandre Reinhardt**

**11:10 Advances in RF SAW Devices: What Are Demanded? (Invited) #1014#**

Ken-Ya Hashimoto
Chiba University, Japan

A large number of surface acoustic wave (SAW) filters are embedded in a current smart phone, and their annual production is several tens of billions. Since total performances of current mobile communications are often limited by those of SAW devices, drastic enhancement of their performances is still strongly demanded in addition to further reduction of physical size and price. This talk reviews current status and future prospect of radio frequency (RF) SAW devices used in mobile communications. Then a survey is given to demands necessary for realization of near future communication systemss.

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**11:50 Elimination of Spurious Modes in Zinc Oxide Resonators #1061#**

Ossama Mortada{2}, Matthieu Chatras{2}, Abedel Halim Zahr{2}, Pierre Blondy{2}, Aurelian Crunteanu{2}, Jean Christophe Orlianges{1}
{1}SPCTS UMR 7513, University of Limoges/CNRS, France; {2}XLIM UMR 7252, University of Limoges/ CNRS, France

We report on the design, simulation, fabrication and test results of micro-resonators integrating piezoelectric ZnO layers. The micro-resonators are built on top of 2µm silicon membranes of SOI-type wafers. We analyze several possibilities of increasing the quality factor Q and the electromechanical coupling coefficient kt2 of the devices, for different numbers and different lengths of inter-digitated (IDTs) electrodes by eleminating the plurality of resonance modes which are mixed together at the main mechanical resonance. IDTs of different finger numbers (N=25, 40, 50 and 80) and lengths (L=25λ, 35λ, 42λ and 50λ) were designed and fabricated. The measured extracted Q confirms that reducing the length and the number of IDTs fingers enables to reach better electrical performances at 700 MHz. Our results show that for an optimized micro-resonator device having a IDTs length of 25λ and 40 finger electrodes, we obtained a Q of 1180 and a kt2 of 7.4%

**12:10 Transparent Thin Film Bulk Acoustic Wave Resonators #1189#**

Mario DeMiguel-Ramos{2}, Girish Rughoobur{2}, Teona Mirea{1}, Bárbara Díaz-Durán{1}, Jimena Olivares{1}, Marta Clement{1}, Enrique Iborra{1}, Andrew Flewitt{2}
{1}Universidad Politécnica de Madrid, Spain; {2}University of Cambridge, United Kingdom

Transparent electronics have interesting applications in the field of electronic consumables. In this work we present fully transparent AlN-based FBARs with a solidly mounted resonator (SMR) structure, fabricated on a glass substrate. The obtained devices display a good performance while keeping a good transparency when placed on a retro-illuminated display.

| **A2P-D** | **Student Paper Competition P/L005** | **Poster Area** |
|---|---|---|
| **Chair** | **Francois Vernotte** | **14:00 – 15:40** |

**Using Known Ground Station Clock Offsets to Improve Tropospheric Delay Estimates at NIMT Timing Station #1008#**

Chaiyaporn Kitpracha{1}, Thayathip Thongtan{3}, Pornchanit Moonaksorn{1}, Rata Suwantong{2}, Chalermchon Satirapod{1}
{1}Chulalongkorn University, Thailand; {2}Geo-Informatics and Space Technology Development Agency, Thailand; {3}National Institute of Metrology Thailand, Thailand

GPS satellite clocks are used as time references for time comparison with receiver clock by a direct measurement of signals from visible satellites. The timing receiver is in a fixed location by applying the Precise Point Positioning algorithm using the Position and Navigation Data Analyst (PANDA) software. When the clock offsets are estimated, the correlations between the estimated station height and the estimated troposphere are existed. This paper shows the estimated tropospheric delay is averagely at 2.5 meters. The repeatability of the station position is at 1 cm vertically.

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**Quantum Logic State Detection for Molecular Ions #1027#**

Fabian Wolf{1}, Yong Wan{1}, Jan Heip{1}, Florian Gebert{1}, Chunyan Shi{1}, Piet Schmidt{2}
{1}Physikalisch-Technische Bundesanstalt, Germany; {2}Physikalisch-Technische Bundesanstalt, Universität Hannover, Germany

Molecules offer fascinating possibilities for fundamental research due to their rich internal structure. The lack of a cycling transition for cooling and detection in most molecules has limited wide-spread applications. While the development of quantum logic techniques for atomic ions has enabled spectroscopy of previously inaccessible species, the application of these techniques to molecular ions is still infeasible. Here, we present the first implementation of non-destructive state detection using quantum logic operations between a molecular and an atomic ion. This result establishes a technique enabling quantum

information processing and high-precision spectroscopy for tests of fun-damental physics with cold molecular ions.

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**Multi-Clock Dissemination via One Ring-Like Fiber Network #1057#**

Wei Chen, Qin Liu, Jialiang Wang, Nan Chen, Fei Yang, Youzhen Gui, Haiwen Cai
Shanghai Institute of Optics and Fine Mechanics,CAS, China

Fiber-based time and frequency dissemination have been developed rapidly to satisfy a higher precision of atomic clocks. In particular, some “multi-users” solutions have been demonstrated to expend its applications. But problem still leaves in multi-clock dissemination and comparison in one simple fiber link. In this paper, we present a novel scheme to distribute ultra-stable frequency signals from different locations with only one active compensation structure. Relative frequency stabilities of 3e-14@1s and and 5e-14@1s for master and slave clock are obtained.This scheme opens the way to simplify a continental clocks comparison network.

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**Elimination of Spurious Modes in Zinc Oxide Resonators #1061#**

Ossama Mortada[2], Matthieu Chatras[2], Abedel Halim Zahr[2], Pierre Blondy[2], Aurelian Crunteanu[2], Jean Christophe Orlianges{1}
{1}SPCTS UMR 7513, University of Limoges/CNRS, France; [2]XLIM UMR 7252, University of Limoges/ CNRS, France

We report on the design, simulation, fabrication and test results of micro-resonators integrating piezoelectric ZnO layers. The micro-resonators are built on top of 2µm silicon membranes of SOI-type wafers. We analyze several possibilities of increasing the quality factor Q and the electromechanical coupling coefficient kt2 of the devices, for different numbers and different lengths of inter-digitated (IDTs) electrodes by eleminating the plurality of resonance modes which are mixed together at the main mechanical resonance. IDTs of different finger numbers (N=25, 40, 50 and 80) and lengths (L=25 λ, 35 λ, 42 λ and 50?) were designed and fabricated. The measured extracted Q confirms that reducing the length and the number of IDTs fingers enables to reach better electrical performances at 700 MHz. Our results show that for an optimized micro-resonator device having a IDTs length of 25 λ and 40 finger electrodes, we obtained a Q of 1180 and a kt2 of 7.4%

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**Frequency Synthesis from Cryogenic Sapphire Oscillator #1043#**

Etienne Vaillant{2}, Fabrice Sthal{2}, Joël Imbaud{2}, Christophe Fluhr{2}, Serge Grop{2}, Vincent Giordano{2}, Enrico Rubiola{2}, François-Xavier Esnault{1}, Gilles Cibiel{1}
{1}CNES, France; {2}FEMTO-ST, France

To characterize ultra-stable resonators, the passive technique with carrier suppression is used to measure the inherent phase stability of the ultra-stable resonators. This kind of bench usually uses both identical resonators inserted in each arm in order to suppress the noise of the source [2]. To operate with only one resonator, the driving source must have a phase noise lower than the best resonators that are measured. At 5 MHz, the power spectral density of phase fluctuations of these best quartz crystal resonators is expected around -140 dBc/Hz. In these conditions, the driving source cannot be an ultrastable 5 MHz quartz oscillator. Cryogenic sapphire oscillators present a very low phase noise [3]. Thus in this paper, first results of frequency synthesis chain from cryogenic sapphire oscillator are presented. A 100 MHz signal is divided until 5 MHz in order to get the best phase noise. Several divider combinations are presented and discussed. The limits of commercial dividers are shown and best results have been obtained using regenerative dividers (Fig. 1). Further investigations are proposed in order to improve these results.

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**High-Performance CPT-Based Cs Vapor Cell Atomic Clock Using Push-Pull Optical Pumping** **#1048#**

Moustafa Abdel Hafiz, Rodolphe Boudot
FEMTO-ST, France

This paper presents a high-performance CPT Cs vapor cell atomic clock using the push-pull optical pumping technique. A fractional frequency stability of 2 10^(-13) up to 100 s has been demnstrated. Latest results will be presented at the conference.

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**Carrier-Envelope Offset Characterization in a Semiconductor Modelocked Laser Without f-to-2f Interferometry** **#1070#**

Pierre Brochard{2}, Nayara Jornod{2}, Valentin Wittwer{2}, Stéphane Schilt{2}, Dominik Waldburger{1}, Sandro Link{1}, Cesare Alfieri{1}, Matthias Golling{1}, Laurent Devenoges{3}, Jacques Morel{3}, Ursula Keller{1}, Thomas Südmeyer{2}
{1}ETH Zurich, Switzerland; {2}Laboratoire Temps-Fréquence, Switzerland; {3}METAS, Switzerland

We measured for the first time the noise properties and the modulation response of the free-running carrier-envelop offset (CEO) frequency in a semiconductor modelocked laser. We used a novel characterization method that does not involve standard f-to-2f interferometry, but makes use of an appropriate combination of signals obtained from the comb and a reference continuous-wave laser. We first present a validation of the method in an Er:fiber comb, where the achieved results are in excellent agreement with reference data obtained by f-to-2f interferometry. Then we present an implementation of the method with a modelocked vertical external-cavity surface-emitting laser.

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**Time Transfer Over a White Rabbit Network** **#1089#**

Namneet Kaur{2}, Paul-Eric Pottie{2}, Philip Tuckey{1}
{1}LNE-SYRTE,Observatoire de Paris, France; {2}SYRTE,Observatoire de Paris, France

A very promising direction for precise time transfer through optical fibers is the implementation of White Rabbit PTP(Precision Time Protocol) technology on wide area networks. This novel technology is based on Synchronous Ethernet and other techniques to achieve high performance. It demonstrates sub-nanosecond time stability and synchronization of arrays of instruments over 10-km scale networks. In view of time dissemination on active telecommunication networks, we are exploring uni-directional configurations for White Rabbit links. Our objective is the development of a scalable and compatible network time transfer approach providing multiple user dissemination, competitive with GNSS-based time distribution.

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**Synchronous Mode-Locked Laser Network with Few-fs Jitter and Multi-km Distance #1095#**

Kemal Safak{1}, Ming Xin{2}, Michael Y. Peng{2}, Franz X. Kärtner{1}
{1}Deutsches Elektronen-Synchrotron, Germany; {2}Massachusetts Institute of Technology, United States

Long-term stable timing transfer between three mode-locked lasers over a multi-km fiber network is reported. Two slave lasers are synchronized to the master laser via a 4.7-km fiber link network using balanced optical cross-correlators. The out-of-loop jitter between the slave lasers shows only 1.4-fs RMS total jitter over 40 hours. This results proves the feasibility of a mode-laser network with 10^-20 relative timing instability.

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**S0 Lamb Wave Resonators for in-Liquid Sensing: Promising Alternative to Shear Bulk Acoustic Wave Devices #1125#**

Teona Mirea{2}, Ventsislav Yantchev{1}, Enrique Iborra{2}
{1}Chalmers University of Technology and Q-Arts Consulting Ltd, Bulgaria; {2}Universidad Politécnica de Madrid, Spain

S0 Lamb wave resonators (S0-LWR) have shown great potential for in-liquid operation. They can be used on a dual quantity sensor platform since they are sensitive to both, mechanical (density and viscosity) and electrical (dielectric permittivity) properties of the liquid. Here we present extensive theoretical and experimental studies on their in-liquid sensing mechanisms. Additionally, we compare them to the commonly used solidly mounted shear mode bulk acoustic wave devices and show their comparable in-liquid performance. This places S0-LWR as promising alternative with the advantage of using commercial c-oriented AlN deposition.

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**Progress on the CPT Clock: Reduction of the Main Frequency Noise Sources#1139#**

Francois Tricot{2}, Sinda Mejri{2}, Peter Yun{2}, Bruno Francois{1}, Jean-Marie Danet{3}, Stephane Guerandel{2}, Emeric De Clercq{2}
{1}INRIM, Italy; {2}LNE-SYRTE, France; {3}SYRLINKS, France

Clocks based on coherent population trapping (CPT) represent promising candidates for on-board space and industrial applications thanks to their simple scheme and high stability performance. Indeed in our CPT clocks the microwave frequency is optically carried into a vapor cell of cesium. We present here the main frequency noise sources for the clock stability, now σy (1s) = 3.2x10-13; and what we are doing to decrease the frequency noise contributions.

**Towards Self Spin-Squeezing in a BEC Atomic Clock #1156#**

Theo Laudat{1}, Vincent Dugrain{2}, Jakob Reichel{2}, Peter Rosenbusch{1}
{1}Observatoire de Paris - SYRTE, France; {2}UPMC, France

State-of-the-art microwave-frequency standards have reached the quantum projection noise limit, and using spin-squeezing is an appealing approach to overcome this fundamental boundary. Spin squeezed states are quite hard to produce in the case of 87Rb spinor condensate as they require to greatly modify the interstate atomic interaction g ↑↓. We present a new method where the system reduces g ↑↓ by itself without user intervention, leading to spontaneous spin squeezing in a BEC clock.

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**Optimized 1f-2f Actively Compensated Frequency Synchronization #1208#**

Xi Zhu{1}, Bo Wang{2}, Chao Gao{2}, Yibo Yuan{1}, Jingwen Dong{2}, Lijun Wang{2}
{1}Department of Physics, Tsinghua University, China; {2}State Key Laboratory of Precision Measurement Technology and Instruments, Tsinghua University, China

To satisfy the Square Kilometre Array (SKA) radio telescope requirements on frequency synchronization, we proposed a 1f-2f actively compensated frequency synchronization system. In the trial test at SKA South Africa site, we found that there is a bump on the Allan variance plots of dissemination stability at the averaging time between 10s and 100s. It is caused by the nonlinear effect of RF components in the system. We optimized the scheme and performed a comparing test of the original and optimized schemes on 50 km fibre spool. In the optimized scheme, the bump on the Allan variance plot almost diminished.

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**Light Shifts Studies in CW and Ramsey Double Resonance Vapor Cell Frequency Standards #1099#**

Mohammadreza Gharavipour{2}, Ivan S. Radojicic{1}, Florian Gruet{2}, Christoph Affolderbach{2}, Aleksandar J. Krmpot{1}, Brana M. Jelenkovic{1}, Gaetano Mileti{2}
{1}Institute of Physics, University of Belgrade, Serbia; {2}Laboratoire Temps-Fréquence, Institut de Physique, Université de Neuchâtel, Switzerland

We report our investigations on the compact high-performance rubidium (Rb) vapor-cell clock based on microwave-optical double-resonance (DR). These studies are done in both DR continuous-wave (CW) and Ramsey-DR schemes, using the same clock physics package. Light-shift effects (intensity and frequency) are studied for different laser frequency detuning, in both CW and Ramsey scheme. In the Ramsey scheme, thanks to the separation of light and microwave interactions in the time domain, light-shift effects are suppressed by more than one order of magnitude. This allows improving the long-term clock stability in the case of Ramsey-DR scheme as compared to CW-DR.

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## Non-Destructive MEMS Atomic Vapor Cells Characterization by Raman Spectroscopy and Image Analysis #1112#

Sylvain Karlen, Jean Gobet, Thomas Overstolz, Jacques Haesler
CSEM SA, Switzerland

The UV decomposition of rubidium azide (RbN3) in metallic Rb and nitrogen (N2) is a very promising approach for wafer-level microfabrication of alkali vapor cell. We report on the use of three innovative and non-destructive methods to characterize the decomposition yield and the buffer gas partial pressures (N2 and Ar) of cells made with this technique: Raman spectroscopy is used as a quantitative method to estimate the N2 pressure inside the cavity; image analysis is used to quantify the amount of metallic Rb in the cell; Raman is used to identify potential residues in the cavities after the decomposition.

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## Mapping Acoustic Field Distributions of VHF to SHF SAW Transducers Using a Scanning Electron Microscope #1109#

Aurelien Godet, Jean-Michel Friedt, Sounkalo Dembele, Nadine Piat, Abdelkrim Khelif, Pascal Vairac, Joel Agnus, Pierre Yves Bourgeois, Gwenhael Goavec-Merou
FEMTO-ST, France

Scanning Electron Microscopy (SEM) is used for mapping the electric field associated with acoustic wave propagation in acoustic resonators and delay lines. Shear wave acoustic field mapping is thus accessible, making SEM a complementary technique to the classical optical mapping restricted to out-of-plane displacement.

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## Atomic Quadrupole Moment Measurement Using Dynamic Decoupling #1158#

Ravid Shaniv, Nitzan Akerman, Roee Ozeri
The Weizmann Institute, Israel

We present a method that uses dynamic decoupling of a multi-level quantum probe " a single 88Sr+ ion " in order to measure electric quadrupole energy shift in the D_(5/2) level. In contrast with typical two-level dynamic decoupling schemes, here we take advantage of the six-fold D_(5/2) Zeeman manifold of equidistant levels and reduce the effect of magnetic field noise. By using our measurement scheme, we were able to measure the quadrupole moment of the D_(5/2) level in 88Sr+ with precision better than that of the previous measurement by an order of magnitude.

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## Build-Up Detection and Level Monitoring by Using Capacitive Glocal Technique #1206#

Fovad Ali Khan, Adnan Yousaf, L.M. Reindl
IMTEK, University of Freiburg, Germany

This paper presents an innovative proof of concept of level monitoring capacitive sensor and build-up detection by using the “Glocal” (global and local) E-fields. The change in the sensitivity of the sensor to detect the build-up on the sensor probe is increased by using local E-fields. An initial prototype sensor with the length of 89.5 mm is developed and tested on various fluids. Finite element method (FEM) analysis is also performed in order to investigate the sensitivity of the proposed sensor in different liquids with various dielectric constants. An analytical model is also presented which estimates the electric field strength between the capacitive elements as a function of level for a single segment.

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**Digital Electronics Based on Red Pitaya Platform for Coherent Fiber Links #1177#**

Andrea Carolina Cárdenas-Olaya{3}, Cecilia Clivati{2}, Alberto Mura{2}, Matteo Frittelli{2}, Enrico Rubiola{1}, Jean-Michel Friedt{1}, Claudio Eligio Calosso{2}
{1}FEMTO-ST Institute, France; {2}INRIM, Italy; {3}Politecnico di Torino - INRIM, Italy

The work present here continues the work developed by Calosso et al. [2] where tracking direct digital synthesizer (DDS) technique for coherent optical links is introduced, using the flexibility of digital implementation. The proposed system implements the tracking DDS and additional DDSs for compensation and monitoring completely digital. In that way, the limitation of the system bandwidth caused by the delay between the components interaction is reduced and therefore the cycle slips are minimized. The system implementation is performed in Red Pitaya, a platform driven by a system on chip (SoC) from Xilinx.

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**Optical to Microwave Synchronization with Sub-Femtosecond Daily Drift #1227#**

Aram Kalaydzhyan{1}, Michael Peng{2}, Franz Kärtner{1}
{1}Center for Free-Electron Laser Science, Germany; {2}Massachusetts Institute of Technology, United States

In this paper we demonstrate that balanced optical-microwave phase detectors (BOMPD) are able to provide a robust long-term optical-RF synchronization with sub-femtosecond residual timing drift over 24 hours in laboratory conditions without active temperature control of optical and electronic paths. Moreover, 10.833 GHz Sapphire-loaded cavity oscillator (SLCO) was successfully disciplined by 216.66 MHz laser oscillator using the BOMPD which resulted in a sub-femtosecond RMS jitter integrated from 1 Hz to 1 MHz.

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**Low Phase Noise 10MHz Crystal Oscillators #1234#**

Tsvetan Burtichelov, Jeremy Everard
University of York, United Kingdom

This paper describes the design and implementation of low phase noise 10MHz Crystal Oscillators which are being used as part of the chain of a local oscillator for use in compact atomic clocks. The design considerations and phase noise measurements are presented. This paper is based on a previous design [1] but now demonstrates significantly improved phase noise performance and now includes the key circuit descriptions. The latest measurements of the 10MHz crystal oscillator's performance demonstrates a phase noise of -123dBc/Hz at 1 Hz and -148dBc/Hz at 10 Hz. The results compare well with the best 5MHz BVA oscillators when 6dB (÷2) is subtracted.

**Brillouin Scattering in a Lithium Fluoride Crystalline Resonator for Microwave Generation #1235#**

Souleymane Diallo, Guoping Lin, Jean Pierre Aubry, Yanne K. Chembo
Femto-ST Institute, France

We report Brillouin lasing in a monofluoride crystalline resonator for the very first time. While Raman scattering results from the interaction between a laser beam and an optical phonon providing a frequency shift in the THz range, Brillouin scattering results from the interaction between a strong laser beam and an acoustic phonon leading to a frequency shift of few GHz, which makes it more suitable for microwave generation. We present a time domain model which tracks the dynamics of the Stokes and pump waves and finally, with the help of a stability analysis, we determine analytically the threshold power. Such a laser has great potential for ultra-pure microwave and multi-wavelength generation.

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**87Sr and 88Sr Optical Lattice Clocks at NPL #1163#**

Ian Hill{1}, Richard Hobson{1}, William Bowden{1}, Marco Menchetti{1}, Antoine Rolland{1}, Fred Baynes{1}, Helen Margolis{1}, Patrick Baird{2}, Kai Bongs{3}, Patrick Gill{1}
{1}NPL, United Kingdom; {2}Oxford, United Kingdom; {3}University of Birmingham, United Kingdom

We present an evaluation of the NPL 87Sr optical lattice clock. The evaluation is aided by an improved stability of the clock, provided by an ultra-stable laser at 1064 nm delivered across a fibre comb-based transfer oscillator scheme to 698 nm. We also present progress towards an accurate 88Sr clock and show the elimination of probe induced shifts using a modified-hyper-Ramsey spectroscopy.

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**State-of-the-Art Ultra-Low Phase Noise Photonic Microwave Generation and Characterization #1171#**

Romain Bouchand{3}, Xiaopeng Xie{3}, Daniele Nicolodi{3}, Pierre-Alain Tremblin{4}, Giorgio Santarelli{4}, Christophe Alexandre{2}, Michele Giunta{5}, Matthias Lezius{5}, Wolfgang Haensel{5}, Ronald Holzwarth{5}, Datta Shubhashish{1}, Joshi Abhay{1}, Yann Le Coq{3}
{1}Discovery Semiconductors, Inc., United States; {2}LNE-CNAM, France; {3}LNE-SYRTE, France; {4}LP2N, France; {5}Menlo Systems GmbH, Germany

Many applications such as telecommunication, radar, deep-space navigation systems and pre-cision microwave spectroscopy are calling for ultra-stable microwave signals. Photonic generation of such signals is of particular interest because it allows transferring the unsurpassed spectral purity of ultra-stable continuous wave lasers to the microwave domain. The conversion from optical to micro-wave is done by synchronization of the repetition rate of a femto-second laser with an ultra-stable op-tical frequency reference. The microwave signal is further extracted via fast photo-detection of the optical pulse train. However, the photo-detection process itself introduces excess phase noise hereby limiting the stability of the optically generated microwave signal. The main limits on the purity of the microwave signal generated are the amplitude-to-phase conversion (APC) combined with intensity noise of the femto-second laser and the shot and thermal noise from the photodetector.

| **A2P-E** | **Frequency References and Measurements** | **Poster Area** |
|---|---|---|
| **Chair** | **Fabrice Stahl** | |

**Recent Development on a Cryogenic Superconducting Cavity Stabilized Oscillator in China** **#1005#**

Nuan-Rang Wang{1}, Zhi Li{2}, Zhen-Wei Zhang{1}, Ren-Fu Yang{1}, Huan Zhao{1}, Lian-Shan Gao{1}
{1}Beijing Institute of Radio Metrology & Measurement, China; {2}Second Academy of China Aerospace, China

The design of cryogenic superconducting cavity stabilized oscillator is achieved based on theory analysis and computer simulation. It includes the design of superconducting cavity with high quality factor, cryogenic environment, PLL and so on. The quality factor of cavity reaches 2E9 and the temperature is 1.6K and the temperature stability is better than 0.001K in experiment. The experiment result is achieved through system debug and optimization that the stability of 1s reaches 4.6E-15 which is the best in ever reported superconducting cavity stabilized oscillator.

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**High Precision Time Interval Measurement Based on Temperature Compensation** **#1067#**

Xiangwei Zhu, Ke Zhang, Zhibin Xiao, Zhicheng Lv, Guangfu Sun
NUDT, China

Time is one of the basic physical quantities which can be measured with high accuracy, especially, the time interval measurement usually possesses accuracy within sub-nanosecond level. Such measurement techniques are widely used in atomic time, satellite navigation, space tracking and control, quantum physics and instruments, etc. It is difficult to perform time interval measurement directly in engineering since system clocks with very high accuracy are required. Hence, several indirect measurement techniques are developed, the most representative approaches are analog interpolation, vernier method and time to amplitude conversion, etc.

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**System of Formation of Reference Frequency for Modern Data Conversion** **#1182#**

Anatoly Kosykh, Konstantin Murasov, Sergey Zavyalov, Rodion Fakhrutdinov, Ruslan Wolf
Omsk State Technical University, Russia

In this paper the system generate a set of reference frequencies required to clock functional blocks of data conversion investigation. The basis of the unit for generating reference frequency is phase-locked loop (PLL), which includes a voltage controlled oscillator on delay

lines, phase-frequency detector, the output frequency of the VCO divider, reference divider and loop filter containing the software-configurable system leakage current compensation.

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**On Temporal Correlations in High Resolution Frequency Counting #1200#**

Tim Dunker{2}, Harald Hauglin{2}, Ole Rønningen{1}
{1}ICTEC AS, Norway; {2}Justervesenet, Norway

We analyse the autocorrelation of time series of gapless frequency data from different high resolution counters. We find that the high resolution (‘CONT’) frequency counting process of the 53230A type counter imposes long term correlations in the output data. We show how such correlations may be due to smoothing processes with long term memory. Finally, we demonstrate how alternative finite window smoothing filters may be applied to a stream of raw (i.e. not smoothed) continuous frequency data, yielding resolution enhanced frequency estimates without spurious long term correlations.

| **A2P-F** | **Piezoelectric Resonators II** | **Poster Area** |
|---|---|---|
| **Chair** | **Marc Faucher** | |

**Thin Film Viscoelastic Losses of a Length Extension Mode Resonator #1046#**

Beatrice Bourgeteau-Verlhac, Pierre Lavenus, Raphael Levy, Jean Guerard, Olivier Le Traon
ONERA, France

We presented in a previous paper a new length extension mode (LEM) piezoelectric micro-resonator. We demonstrated that thanks to a specific design anchor losses were very low, showing the Q.f product could be maximized. Assuming viscous fluid damping and thermoelastic damping are negligible, it appears that viscous damping arising from the gold electrodes is the only remaining limiting loss. Assuming a Kelvin Voigt viscoelastic behavior of gold the quality factor expected is lower than previous LEM resonators. From this consideration a study is being carried out on new electrode designs to reduce viscoelastic damping finding a compromise between motional resistance and quality factor and to improve the vicoelastic modeling of electrodes.

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### In-situ Characterization of AlN-Solidly Mounted Resonators at High Temperature #1186#

Teona Mirea, Jimena Olivares, Marta Clement, Bárbara Díaz-Durán, Jesús Sangrador, Enrique Iborra
Universidad Politécnica de Madrid, Spain

Surface acoustic wave devices are widely investigated for high temperature applications. However they still present the drawback of using long and narrow metallic strips for their IDT, which are subjected to destructive agglomeration. In a previous work we proved that solidly mounted resonators (SMR) are promising alternative standing temperatures as high as 700°C in vacuum without degradation in performance after annealing. Here we present in-situ measurements of AlN-based SMR for temperatures up to 400°C. We show that devices maintain a constant temperature coefficient of frequency and their performance is almost preserved with a series resistance degradation due to measurement fixtures.

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### Behavior of Quartz Crystal Resonators at Liquid Helium Temperature #1217#

Serge Galliou{1}, Philippe Abbé{1}, Maxim Goryachev{2}, Eugene Ivanov{2}, Michael Tobar{2}, Roger Bourquin{1}
{1}FEMTO-ST Institute, France; {2}UWA, Australia

Quartz resonators working at cryogenic temperature are an exciting topic of interest because of their very high quality-factors. As a consequence they are good candidates to various applications ranging from frequency references to fundamental physics. A brief reminder is first provided regarding Q-factor properties of BAW SC-cut resonators within 3K - 12K. The A, B and C mode behaviors are also examined in terms of frequency versus temperature. As unpublished data, the frequency dependence with the excitation power is particularly highlighted. Finally recent measurements on noise are discussed.

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|---|---|---|
| **A2P-G** | **Microwave Frequency Standards & Applications I** | **Poster Area** |
| **Chair** | **Patrick Berthoud** | |

### Development of an Atomic Interferometer Utilizing the Stimulated Raman Transition #1006#

Sangkyung Lee, Tae Hyun Kim, Sin Hyuk Yim, Hee Sook Ro, Kyu Min Shim
Agency for Defense Development, Korea, South

We demonstrate an atomic interferometer utilizing cold atoms and the stimulated Raman transition to measure acceleration of gravity. To improve performance of an atomic interferometer, the optical pumping to populate the free-falling atoms in the magnetic insensitive state and normalization of atomic population by using the three pulsed probe scheme are applied. The interference fringes are obtained as a function of linear chirp rates of Raman detuning. We also introduce our progresses on development of an atomic interferometer for rotation measurement.

## Coherent Population Trapping Ramsey Resonance in Slow Rubidium Beam #1015#

Igor Sokolov
Peter the Great St. Petersburg Polytechnic University, Russia

We calculate the coherent population trapping (CPT) resonance in slow beam of rubidium 87 atoms caused by their interaction with bichromatic electromagnetic field in two separated spatial domains. We study the influence of the atomic beam angular divergence and residual beam velocity spread on the parameter of CPT resonance. The dependence of the profile of the resonance on principal parameters of the system is analyzed.

## Effects of Microwave Leakages on the Frequency Shift of Compact Magnetic Selection State Cesium Atom Clock #1039#

Liangyu Huang, Ji Wang, Hongwei Zhu, Ning Zheng, Dapeng Cheng, Jiang Chen, Jun Yang
Lanzhou Institute of Space Technology and Physics, China

This paper discusses the relationship between the microwave leakages in the different positions and frequency shifts.The theoretical results show that the leakage taken place outside the interaction area is the one of key reasons to the frequency shift. With the same parameters, the influence of the leakage occurred inside of the interaction area is three order of magnitude smaller than the outside.

## A Novel Alkali Vapor Microcell Architecture for Miniature Atomic Clocks #1050#

Vincent Maurice{1}, Ravinder Chutani{1}, Nicolas Passilly{1}, Rodolphe Boudot{2}, Serge Galliou{1}, Moustafa Abdel Hafiz{1}, Philippe Abbé{1}, Emeric De Clercq{3}, Christophe Gorecki{1}
{1}FEMTO-ST, France; {2}FEMTO-ST - CNRS, France; {3}LNE-SYRTE, France

This work presents a new and original architecture of microfabricated alkali vapor cell designed for miniature atomic clocks. The cell combines diffraction gratings with anisotropically etched single crystalline silicon sidewalls to route a normally-incident beam in a cavity oriented along the substrate plane.

## Preparation of High Purity Cesium by Molecular Distillation #1055#

Yinguang Ma, Jiang Chen, Ji Wang, Liangyu Huang, Hongwei Zhu, Jun Yang
Lanzhou Institute of Physics, China

A novel technique was developed to purify 99.5% cesium by molecular distillayion to meet the stringent requirement of Cesium-Atomic-Clock.The results show that depending on the purification conditions, most impurities of K and Rb were removed. We suggest that the molecular distillation may outperform the conventional vacuum distillation because of a lower temperature and s shorter time.

**Study of the Misalignment Between Electromagnetic Fields Interacting with Rb Atoms in a Cavity with Losses** **#1072#**

Anton E. Ivanov{1}, Christoph Affolderbach{2}, Gaetano Mileti{2}, Anja K. Skrivervik{1}
{1}École Polytechnique Fédérale de Lausanne, Switzerland; {2}University of Neuchâtel, Switzerland

In this study we investigate the impact of misalignment of the static and/or microwave magnetic fields from the laser propagation direction. Our analysis is suitable to reveal how the geometry of the cavity and the losses influence the resonance transitions and is relevant in line with newly developed cavity characterization techniques based on field imaging.

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**Research of Cesium Atom Clock Beam Intensity Associated with Collimator Structure** **#1081#**

Hongwei Zhu, Jiang Chen, Ji Wang, Yinguang Ma, Liangyu Huang, Jun Yang
Lanzhou Institute of Space Technology Physics, China

Beam intensity of cesium atom emanated from collimator directly affected performance of cesium atom clock. This thesis analyzed the process of cesium atom emanated from collimator, established theoretical beam distribution model based on reflection of the atom from the walls of the collimator tube, beam distribution related with structure and dimension of collimator. The thesis adopted simulative calculation method and experiment to prove theoretical model. The investigation guided collimator design to improve cesium atom beam intensity and short term stability of cesium atom clock.

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**High-Contrast Bright-Type Magneto-Optical Resonances in Buffer-Gas or Antirelaxation-Coated Vapour Cells** **#1092#**

Denis Brazhnikov{2}, Maxim Basalaev{4}, Alexey Novokreshchenov{2}, Alexey Taichenachev{2}, Valeriy Yudin{4}, Christina Andreeva{1}, Vasiliy Entin{3}, Igor Ryabtsev{3}
{1}Institute of Electronics, Bulgaria; {2}Institute of Laser Physics SB RAS, Russia; {3}Institute of Semiconductor Physics SB RAS, Russia; {4}Novosibirsk State University, Russia

New method for observing magneto-optical electromagnetically induced absorption resonance (EIA) is theoretically and experimentally studied. We propose new scheme that allows us using buffer gas or antirelaxation-coated cells for dramatically improving properties of the resonance in contrast to the standard schemes. Under the special conditions contrast of EIA resonance can reach value of about 95% and kHz or even sub-kHz width. In the new scheme EIA effect resulted from the coherent population trapping phenomenon (CPT), which regularly leads to electromagnetically induced transparency (EIT). It opens new opportunities for applying the scheme in nonlinear optics, quantum magnetometry and optical communications.

**Recent Results of an Atomic Gravimeter Developing at KRISS #1111#**

Sang-Bum Lee, Taeg Yong Kwon, Sang Eon Park, Myoung-Sun Heo, Hyun-Gue Hong, Chang Yong Park, Won-Kyu Lee, Dai-Hyuk Yu
KRISS, Korea, South

We will introduce recent results of an atomic gravimeter developing at KRISS and also discuss about limiting elements affecting the sensitivity of our gravimeter at this conference.

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**Quantum Tests of the Universality of Free Fall #1132#**

étienne Wodey, Henning Albers, Hendrik Heine, Christian Meiners, Logan L. Richardson, Dipankar Nath, Dennis Schlippert, Christian Schubert, Wolfgang Ertmer, Ernst M. Rasel
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The universality of free-fall (UFF) is at the foundation of our current understanding of gravity through Einstein's general relativity theory. However, theoretical attempts to reconcile general relativity with quantum field theory allow for violations of the UFF. We report on a quantum test of the UFF at the 100 ppb level by performing atom interferometry with two chemically different species. We also present our strategies to advance quantum tests of the UFF to the level of the best classical tests and beyond using very long baseline atom interferometers.

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**Hydrogen Plasma Simulation for Atomic Clock Lifetime Assessment #1134#**

Eleonie van Schreven, Marco Belloni
ESA (European Space Agency), Netherlands

Passive Hydrogen Masers are currently embarked onboard of Galileo constellation and are showing outstanding performances.However, given the lack of statistic over lifetime, parallel activities are ongoing for analyzing possible failure mechanisms and improve the robustness. The present work presents a simulation model based on COMSOL Multiphysics, investigating the wear-out effects experienced by the hydrogen gas dissociator.

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**Optimization of Laser Radiation for CPT-Based Miniature Frequency Standard #1147#**

Konstantin Barantsev, Andrey Litvinov, Evgeniy Popov, Igor Sokolov
Peter the Great St.Petersburg Polytechnic University, Russia

In this work we investigate dependence of stability of the CPT-based miniature frequency standard on parameters of the laser radiation such as total intensity, ratio between sideband intensities, polarization and tuning of each sideband, width of the spectrum and correlation of sidebands.

**VNIIFTRI Primary Frequency Standard: Current Status** **#1213#**

Igor Blinov, Alexandr Boyko, Yuri Domnin, Dmitrii Kupalov, Olga Kupalova
FGUP VNIIFTRI, Russia

National Frequency Standard of Russia, SU-CsFO2, has been in use since 2012 [1]. CsF02 is used for the local representation of the UTC maintained by SU. To date, 18 calibrations of the International Atomic Time (TAI) have been reported to BIPM with a relative frequency agreement of (-0.7±4.5) •10-16, between CsFO2 and the average of the other fountains operated in the world in the reference periods. Accuracy evaluations have enabled its type B uncertainty to be reduced to 2.5•10-16, taking into account improved evaluation of the microwave power dependence shift, the distributed cavity phase shift and collision shift. Our conference paper will update our progress towards the SU-CsFO2 accuracy evaluation.

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**The Optical Feedback Spatial Phase Driving Perturbations of DFB Laser Diodes in an Optical Clock** **#1219#**

Roman Schmeissner{2}, Nicolas von Bandel{1}, Michel Garcia{1}, Michel Krakowski{1}, Michel Baldy{2}
{1}III-V Lab, France; {2}Thales Electron Devices, France

It is shown that the sensitivity of DFB laser diodes to low-level back-reflections significantly depends on the spatial phase of the reflected beam, i.e. the surface roughness of the reflecting element. Laser diodes of different suppliers are compared. Impacts on optical clock operation are studied based on the optical hyperfine pumping principle.

| **A2P-H** | **Timekeeping, Time & Freq Transfer, GNSS Apps I** | **Poster Area** |
|---|---|---|
| **Chair** | **Peter Whibberley** | |

**Characterization of the Frequency Transfer Over 300 km of Aerial Suspended Fiber** **#1009#**

Lukasz Sliwczynski{1}, Przemyslaw Krehlik{1}, Krzysztof Turza{2}, Artur Binczewski{2}
{1}AGH University of Science and Technology, Poland; {2}Pozna ń Supercomputing and Networking Center, Poland

In this paper we are reporting on the experiments with a 300 km long suspended fiber running inside the safety wire of the power grid and carrying the 10 MHz frequency signal. Basing on performed measurements we determined diurnal delay changes, maximum slope of delay change as well as the dynamics of the fluctuation changes within the day.

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**Real-Time Performance Monitoring of Fiber Optic Longdistance Time and RF Frequency Transfer Links** **#1010#**

Lukasz Sliwczynski, Przemyslaw Krehlik
AGH University of Science and Technology, Poland

In this paper we propose the new idea based on monitoring of the performance of bidirectional fiber link in a real time. The key element for this is a circuit for measuring the jitter of RF the signal. The operation and parameters of developed circuit that is able to measure accurately the jitter in the full bandwidth of interest will be presented. Us-ing proposed idea and developed circuits it will be possible to realize the distributed control system to trim the gains of SPBAs automatically to into the optimum operation, even when the parameters of the fiber path changes (e.g. due to fiber break or other modifications).

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**Fiber-Optic Time Distribution with the Autonomous Calibration of Dispersion-Induced Offset** **#1013#**

Przemyslaw Krehlik, Lukasz Sliwczynski
AGH University of Science and Technology, Poland

In this work we will describe a new and precise method of determining the dispersion-caused offset in fiber-optic time distribution system ELSTAB. Obtained results will be compared with dispersion estimation based on the fiber vendor’s data, and measured with standard dispersion measurement devices used in optical tele-communication. As will be proved, application of this new method allows obtaining absolute calibration of the timescale delay with uncertainty less than 20 ps.

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**Comparison of Different Amplification Concepts for Multiple Point Frequency Dissemination** **#1026#**

Alexander Kuhl, Thomas Waterholter, Jan Froh, Gesine Grosche
Physikalisch-Technische Bundesanstalt, Germany

We present a comparison of different amplification concepts for the dissemination of an ultra stable frequency to different sites simultaneously. We extend an already available fiber link to provide an optical signal at 3 institutes located at a distance of about 73 km. At each site a fraction of the signal power is extracted from the link. Since the increased loss due to the modification of the link setup requires a different amplification scheme, we will investigate and compare different approaches by using either bidirectional erbium-doped fiber amplifiers or fiber Brillouin amplification.

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**Pilot Comparison of Time Interval Measurements with High Speed Oscilloscopes - Initial Results** **#1044#**

Alexander Kuhl, Thomas Waterholter, Jan Froh, Gesine Grosche
Physikalisch-Technische Bundesanstalt, Germany

In this paper we present the initial results of the pilot comparison of time interval measurements with high speed oscilloscopes being the part of the EURAMET Project #1288. This comparison is aimed to better characterise the electronic based Time Interval Generator as a time interval standard for a new Inter-Laboratory Comparison planned as a Supplementary Comparison in the KCDB. The results are matched very well and contained within the range better than ± 10 ps around each measured value of time interval " up to about 12 us.precise time interval, comparison, picosecond resolution .

**Remote Atomic Clock Delivery to the VLBI Station in Torun** **#1058#**

Przemyslaw Krehlik{1}, Waldemar Adamowicz{5}, Artur Binczewski{6}, Wojbor Bogacki{6}, Lukasz Buczek{1}, Bob Campbell{3}, Roman Ciurylo{4}, Piotr Dunst{2}, Jacek Kolodziej{1}, Dariusz Lemanski{2}, Marcin Lipinski{1}, Andrzej Marecki{4}, Jerzy Nawrocki{2}, Paweł Nogas{2}, Tadeusz Pawszak{5}, Eugeniusz Pazderski{4}, Janusz Pieczerak{5}, Maciej Stroinski{6}, Lukasz Sliwczynski{1}, Krzysztof Turza{6}, Michał Zawada{4}

{1}AGH University of Science and Technology, Poland; {2}Astrogeodynamic Observatory (AOS), Borowiec, Poland; {3}Joint Institute for VLBI ERIC Radiosterrenwacht, Netherlands; {4}Nicolaus Copernicus University, Poland; {5}Orange Polska S.A., Poland; {6}Poznan Supercomputing and Networking Center, Poland

On 26th Nov. 2015 Toruń Radio Astronomy Observatory (based in Piwnice near Toruń, Poland) was connected to Polish fiber optic network distributing time and frequency (T&F) signals from UTC(PL) and UTC(AOS) laboratories. The first proof-of-concept VLBI observation using remote synchronization via optical fiber link was successfully performed and will be reported.

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**OPTIME - Final Release** **#1068#**

Przemyslaw Krehlik{1}, Waldemar Adamowicz{5}, Artur Binczewski{6}, Wojbor Bogacki{6}, Lukasz Buczek{1}, Bob Campbell{3}, Roman Ciurylo{4}, Piotr Dunst{2}, Jacek Kolodziej{1}, Dariusz Lemanski{2}, Marcin Lipinski{1}, Andrzej Marecki{4}, Jerzy Nawrocki{2}, Paweł Nogas{2}, Tadeusz Pawszak{5}, Eugeniusz Pazderski{4}, Janusz Pieczerak{5}, Maciej Stroinski{6}, Lukasz Sliwczynski{1}, Krzysztof Turza{6}, Michał Zawada{4}

{1}AGH University of Science and Technology, Poland; {2}Astrogeodynamic Observatory (AOS), Borowiec, Poland; {3}Joint Institute for VLBI ERIC Radiosterrenwacht, Netherlands; {4}Nicolaus Copernicus University, Poland; {5}Orange Polska S.A., Poland; {6}Poznan Supercomputing and Networking Center, Poland

The document describes the final stage of OPTIME project " which created a self-calibrating, high precision disseminating system for time and frequency reference signal based on optical fiber links. The OPTIME system reached in Poland about 800 km.

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**Optical Two-Way Time Transfer with Picoseconds Accuracy Over Telecommunication Fiber** **#1077#**

Jan Kodet{3}, Petr Panek{1}, Ivan Prochazka{2}, Ulrich Schreiber{3}

{1}Academy of Sciences of the Czech Republic, Institute of Photonics and Electronics, Czech Rep.; {2}Czech Technical University in Prague, Czech Rep.; {3}Technische Universität München, Germany

We have developed a new Two-Way Time Transfer (TWTT) system implementing standard optical telecommunications Small Form-factor Pluggable (SFP) transceivers to transfer timing

information between two or more terminals with the accuracy of the order of 1 ps via optical fibers of the length up to several tens of kilometers. The heart of the measurement technique is an event timing device using a surface acoustic wave filter as a time interpolator, which allows registration of the times-of-arrival of pulses with sub-picosecond timing resolution, linearity and stability. These pulses are derived from the optical signal which is used for communication between the terminals.

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**Verification of Time Signals** **#1080#**

Matthias Schneider, Christoph Ruland
University of Siegen, Germany

In every data network the current system time has to be available in any devices. Most time signals are transmitted via continuous simplex terrestrial broadcast radio links. Such a continuous time signal data stream can also be generated or manipulated by "man-in-the-middle" attacks. This paper describes a method to verify received time signals for different existing time transmission systems. The existing transmission protocols of the time signal transmitter have not to be changed for the integration of this verification approach, because the verification of the time signals will only take place in the receiver.

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**WR-ZEN: Ultra-Accurate Synchronization SoC Based on Zynq Technology** **#1082#**

Miguel Jimenez-Lopez{2}, Emilio Marin Lopez{1}, Rafael Rodriguez{1}, Javier Diaz{2}
{1}Seven Solutions, Spain; {2}University of Granada, Spain

Recently, the White-Rabbit technology has been proposed as alternative to provide deterministic sub-nanosecond synchronization using Gigabit Ethernet standard. In this contribution, we present a new synchronization node based on the Zynq Technology. It allows sub-nanosecond time transfer using a SoC with Linux OS support, providing improved debugging and management capabilities. We describe in detail a new clocking scheme, aspects of the OS customization, kernel modules, user-space tools and the support of additional FMC cards, clearly stating the benefits of the presented approach compared with previous FPGA based WR platforms. Finally, we present experimental results and validation of the timing features.

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**Avoiding Aliasing in Fiber Link Data Analysis** **#1143#**

Claudio Eligio Calosso, Cecilia Clivati, Salvatore Micalizio
INRIM, Italy

In optical fiber link ultrastable frequency transfer, signals are affected by phase noise up to bandwidths of kilohertz and a careful data processing is required to properly estimate the uncertainty. This aspect is often overlooked and a number of approaches have been proposed to implicitly deal with it. Here, we face this issue in terms of aliasing and show how typical tools of signal analysis can be adapted to the evaluation of optical fiber links performance. In this way, it is possible to use the Allan variance as estimator of stability and there is no need to introduce other estimators.

**Sequential Measurement of Optical Frequency Difference of Semiconductor Lasers for Time Transfer System** **#1215#**

Łukasz Buczek
AGH University of Science and Technology, Poland

The stability and accuracy of optical time transfer system (OTTS) depends, among other factors, on optical frequency difference between forward and backward direction laser transmitters. This document describes the concept of precise measuring the difference of optical frequency of two semiconductor lasers spaced 100 GHz apart and more. This method exploits two auxiliary adjustable semiconductor lasers and three high-speed photodiodes.

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**Local Clocks Quality Evaluation Subsystem** **#1233#**

Ryszard Szplet, Krzysztof Rózyc, Pawel Kwiatkowski, Zbigniew Jachna
Military University of Technology, Poland

We propose a novel Clocks Evaluation Subsystem (CES) for continuous verification of parameters of local clocks. The main aim of the CES is to gather information about time drift of the clocks, then to evaluate their stability, and finally to select the most stable one as a local reference clock. In this paper we present the design and operation of the CES, as well as test results that include, among others, the TIC precision evaluation and clocks drift.

| A2P-J | Optical Frequency Standards & Applications I | Poster Area |
|---|---|---|
| Chair | Helen Margolis | |

**UV Laser System for Rydberg Spin-Squeezing in a Strontium Optical Lattice Clock #1045#**

Elizabeth Bridge, Niamh Keegan, Alistair Bounds, Ryan Hanley, Riccardo Faoro, Paul Huillery, Danielle Boddy, Daniel Sadler, Matthew Jones
Durham University, United Kingdom

Spin-squeezing in an optical lattice clock has the potential to reduce the instability below the limit imposed by standard quantum projection noise. We have previously presented a proposal for using the interactions between Rydberg atoms to provide a high degree of spin-squeezing. Here we present the design and characterisation of a UV laser system for Rydberg spin-squeezing in a strontium optical lattice clock.

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**The Optical 88Sr Lattice Clocks and Stabilized Fibre Links: a Frequency Reference for the VLBI System Over 15.5 km Link and an Absolute Measurement of the Clock Transition Over 330 km Link #1059#**

Piotr Morzynski{3}, Marcin Bober{3}, Przemyslaw Krehlik{1}, Lukasz Sliwczynski{1}, Marcin Lipinski{1}, Eugeniusz Pazderski{3}, Andrzej Marecki{3}, Jerzy Nawrocki{2}, Piotr Ablewski{3}, Roman Ciurylo{3}, Michal Zawada{3}
{1}AGH University of Science and Technology, Poland; {2}Astrogeodynamical Observatory of Space Research Center, Poland; {3}Nicolaus Copernicus University, Poland

The 15.5 km-long stabilized fibre optic link between KL FAMO and Toruń Centre for Astronomy made possible to use the strontium optical lattice clocks as a frequency reference for the 32 m radio telescope participating in the VLBI networks. The absolute frequency of the 88Sr clock transition was with reference to the UTC(AOS) via the 330 km-long stabilized fibre optic link of the OPTIME network. We present current status of the KL FAMO optical lattice clocks, including their frequency stability of 7×10-17, the uncertainty budget and the measured absolute frequency of the 1S0-3P0 clock transition.

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**An EOM with Ultra-Low Residual Amplitude Modulation #1084#**

Zhaoyang Tai, Lulu Yan, Yanyan Zhang, Long Zhang, Haifeng Jiang, Shougang Zhang
NTSC, China

We present a new approach to make an electro-optic modulator (EOM) with ultra-low residual amplitude modulation (RAM). Compared with commonly-used methods of actively control RAM with complicated feedbacks, this approach is simple, reliable and easy to realize. We evaluate the performance of such an EOM by setting it into a standard PDH frequency-stabilization system, and compare with that of a commercial one. Error signals of the setup using the home-made EOM is more stable than the other under same measurement conditons, and its Allen deviation is one order in magnitude lower at 1s.

**High-Bandwidth Large-Dynamic Frequency Control of an Optical Comb by Tuning Polarization State** **#1086#**

Yanyan Zhang{2}, Lulu Yan{1}, Songtao Fan{2}, Maoqiang Chen{2}, Wenge Guo{3}, Shougang Zhang{1}, Haifeng Jiang{1}
{1}Key Laboratory of Time and Frequency Primary Standards, National Time Service Center, China; {2}National Time Service CenterGraduate University of Chinese Academy of Sciences, China; {3}School of Science, Xi'an Shiyou University, China

We report a servo control method to stabilize comb's frequencies by changing polarization with a home-made intra-cavity electro-optic modulator (EOM). The EOM is inserted right after the PBS of a well-known nonlinear polarization rotation mode-locked laser`s loop. The EOM rotates state of polarization about 1.2×10-4 rad/V in ellipticity. The frequency con-trol dynamic range of the frequency comb is two orders of magnitude larger than the tradi-tional intro-cavity EOM method, because it benefits from birefringence of the whole cavity instead of only index change of an EOM crystal driven by tunable electric-field. No side effect is observed during experiments.

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**Design of Clock Laser with 10^-16 Frequency Stability for Rapid Uncertainty Evaluation of Yb Lattice Clock** **#1107#**

Won-Kyu Lee, Chang Yong Park, Sang Eon Park, Myoung-Sun Heo, Huidong Kim, Dai-Hyuk Yu
Korea Research Institute of Standards and Science, Korea, South

A clock laser system with 10^16 relative frequency stability is designed to enable rapid uncertainty evaluation of KRISS Yb optical lattice clock. A ULE cuboid-type 30-cm-long cavity is adopted with fused silica mirrors and mirror coating material with low thermal noise. The vertical, longitudinal, transverse vibration sensitivity is calculated by finite element analysis to determine the optimum support position.

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**A Cryogenic Lattice Clock at PTB** **#1121#**

Won-Kyu Lee, Chang Yong Park, Sang Eon Park, Myoung-Sun Heo, Huidong Kim, Dai-Hyuk Yu
Korea Research Institute of Standards and Science, Korea, South

We report on the implementation of a cryogenic optical lattice clock based on the 1S0 " 3P0 transition of Sr-87 at PTB in order to overcome the limitation to systematic uncertainty of 2E-17 due to our knowledge of the effective blackbody radiation (BBR) field. Several groups have already demonstrated approaches to control the BBR-induced frequency shifts to the level of few 1E-18 and less. We present an upgrade of our existing clock with a separate cryogenic interrogation environment and a revised physics package designed to enable systematic uncertainties below 1E-18.

## Sensitivity to a Variation of me/mp from Splittings Between 12C2HD Reference Frequencies #1126#

Florin Lucian Constantin
CNRS, France

A small frequency splitting between acetylene reference lines have an enhanced sensitivity coefficient to a variation of μ. The absolute measurement of a temporal drift of a splitting with potentially smaller systematic uncertainties may probe unambiguously a variation of μ. The sensitivities to a variation of μ of 12C2HD reference transitions are calculated within the Born-Oppenheimer approximation using a four-level effective rovibrational Hamiltonian. The sensitivities to a variation of μ of the molecular parameters, issued from experimental data, are discussed. Pairs of transitions splitted by GHz-level frequency gaps with sensitivity coefficients in the range of ±10^3 are identified.

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## Design, Modelling and Characterization of a Single-Ion Endcap Trap with Minimized Ion-Environment Interaction #1144#

Charles Baynham{5}, Peter Nisbet-Jones{3}, Steven King{3}, Jonathan Jones{4}, Rachel Godun{3}, Kai Bongs{1}, Miroslav Doležal{2}, Petr Balling{2}, Patrick Gill{3}, Patrick Baird{6}
{1}Birmingham University, United Kingdom; {2}Czech Metrology Institute, Czech Rep.; {3}National Physical Laboratory, United Kingdom; {4}National Physical Laboratory / Birmingham University, United Kingdom; {5}National Physical Laboratory / Oxford University, United Kingdom; {6}Oxford University, United Kingdom

A single-ion endcap trap has been designed, built and tested with the demanding needs of cutting edge optical frequency metrology in mind. FEM modelling and subsequent characterisation show that trap exhibits a high quadrupole efficiency, low ion heating rate and well defined BBR environment. Due to the trap's strong environmental isolation and low perturbations, the ion's environment closely approximates an ideal, isolated quantum system. When interrogating a trapped Yb+ ion on its forbidden electric octupole transition for use as a frequency standard, the trap-based contributions to the transition's fractional frequency uncertainty total 3.5x10-19 for typical operating conditions.

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## Testing a Temperature-Stabilized Spectroscopy Chamber for an Optical Lattice Clock Suppressing the Uncertainty of Blackbody Radiation Shift #1153#

Chang Yong Park, Won-Kyu Lee, Dai-Hyuk Yu, Myoung-Sun Heo, Huidong Kim
KRISS, Korea, South

In this presentation we will introduce the preliminary test result of a (171)^Yb optical lattice clock adopting the blackbody-like spectroscopy chamber near room temperature for reducing BBR shift uncertainty, however the temperature of it will be controlled actively. The chamber was designed to have temperature sensors and a heater mounted outside of vacuum chamber for the convenience of calibration of RTD sensors and ultra-high vacuum operation. We have made a test with a copper dummy chamber for temperature homogeneity of it during its temperature was stabilized.

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**Active Optical Standards Using Cold Atoms: Lasing Regimes and Instabilities**
**#1165#**

Georgy Kazakov, Thorsten Schumm
Vienna University of Technology, Austria

The bad cavity regime of laser operation is characterized by the gain profile being narrower than the linewidth of the cavity mode. The frequency of the emitted radiation of such lasers is robust with respect to fluctuations of the cavity length, which opens the possibility to create a highly stable active optical frequency reference on the basis of such a bad cavity laser. Such a laser may have mHz linewidth and short-term frequency stability better than achievable with modern ultrastable cavity-based frequency references. We investigate the bad cavity laser signal for various configuration. We study how the multi-level structure of real atoms and various inhomogeneous effects influence the main properties of the bad cavity lasers, such as the cavity pulling coefficient, output power and the linewidth. We investigate also the stability domains for cw lasing for various atomic configurations in the presence of different inhomogeneous effects.

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**Stabilization of a SESAM Mode-Locked Erbium Laser Frequency Comb with an Integrated Electro-Optic Modulator to an Optical Reference** **#1166#**

Sebastian Schweyer{3}, Philipp Putzer{1}, Eder Bastian{1}, Andreas Kölnberger{1}, Maximilian Breuer{1}, Norbert Lemke{1}, Alexander Sell{5}, Armin Zach{5}, Reinhard Kienberger{4}, Ulrich Schreiber{2}, Urs Hugentobler{2}
{1}OHB System AG, Germany; {2}Technische Universität München, FESG, Germany; {3}Technische Universität München, FESG, Physik Department E11, Germany; {4}Technische Universität München, Physik Department E11, Germany; {5}TOPTICA Photonics AG, Germany

Intra-cavity electro-optic modulators (EOM) show a high performance for stabilizing fiber frequency combs to a narrow linewidth laser. Here a polarization maintaining (PM) SESAM mode-locked all in fiber Erbium laser frequency comb oscillator with an integrated waveguide EOM is stabilized to a HeNe laser leading to a significant linewidth narrowing. In another experiment the EOM comb oscillator was stabilized to a low noise femtosecond oscillator at 1560 nm using the balance optical cross correlator technique. Hereby the timing jitter between the optical pulse trains of both femtosecond lasers was reduced below the 1 fs area.

**An Optical Lattice Clock Based on 24Mg #1183#**

Dominika Fim, Steffen Rühmann, Klaus Zipfel, Nandan Jha, Steffen Sauer, André Kulosa, Wolfgang Ertmer, Ernst Maria Rasel
Leibniz Universität Hannover, Germany

We will report on the determination of the magic wavelength which is 468.46(21) nm and the quadratic magnetic Zeeman shift of -206.6(2.0) MHz/T2 [1], which will be our main systematical shift. We also give an report on the current status of the experiment with an, in terms of power, enhanced lattice and thereby reduced clock transition linewidth by at least two orders of magnitude. [1] A.P. Kulosa et al., Phys. Rev. Lett. 115, 240801 (2015)

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**Towards an Yb+ Optical Clock with a BBR Uncertainty Below 1x10^-18 #1197#**

Jonathan Jones{1}, Rachel Godun{1}, Steven King{1}, Peter Nisbet-Jones{1}, Charles Baynham{1}, Thomas Fordell{4}, Tuomas Hieta{4}, Thomas Lindvall{4}, Kai Bongs{2}, Patrick Baird{3}, Patrick Gill{1}
{1}National Physical Laboratory, United Kingdom; {2}University of Birmingham, United Kingdom; {3}University of Oxford, United Kingdom; {4}VTT Technical Research Centre of Finland, Finland

The authors will present recent measurements of the differential polarizability of the Yb+ clock transitions. The measurements are made by measuring the Stark shift of the clock transition while the ion interacts with off resonant IR light, at a number of wavelengths. Once analysis is completed, this should reduce the BBR uncertainty of the E3 transition to well below 1E-17 - in line with the other systematics of this system.

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**Blackbody-Radiation Shifts of Ytterbium Optical Lattice Clocks #1202#**

Yilin Xu, Min Zhou, Xiaohang Zhang, Qi Gao, Chengyin Han, Peng Xu, Shangyan Li, Shuang Zhang, Xinye Xu
East China Normal University, China

Recently, the rapid developments of the optical lattice clocks make us concern about the blackbody-radiation (BBR) shift, which is resulted from the residual electric field around the cold atoms. Here we propose a new method for estimating blackbody-radiation shift and uncertainty in the 171Yb optical lattice clocks by numerically simulating the temperature distribution around the cold ytterbium atoms based on the measured temperatures on the surface of the vacuum chamber. This new method will be very helpful for precisely evaluating the BBR shift and uncertainty of the optical lattice clocks without the sensors inside the chamber.

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**Optical Quenching of Bosonic Magnesium #1212#**

Steffen Sauer, Steffen Rühmann, Dominka Fim, Klaus Zipfel, Nandan Jha, André Kulosa, Wolfgang Ertmer, Ernst Rasel
Institut für Quantenoptik, Leibniz Universität Hannover, Germany

We report on the progress towards optical quenching of the narrow $3^1S_0 \rightarrow 3^3P_1$ intercombination line in 24Magnesium. The two-photon process couples the $3^3P_1$ state to

the energetically higher state $4^1S_0$, followed by spontaneous decay to the $3^1S_0$ ground state. This gives rise to a quasi two-level-system with faster decay rate of the $3^3P_1$ state, adjusted via the quench laser intensity at 462 nm. With this technique applied to optically trapped magnesium atoms, we expect to demonstrate cooling temperatures of a few µK.

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**New Insights on the Determination of the Linewidth of Low-Noise Signals with the Emergence of a Coherent Peak** **#1220#**

Pierre Brochard, Stéphane Schilt, Thomas Südmeyer
Laboratoire Temps-Fréquence, Switzerland

We present a detailed investigation of the transition between a finite- and zero-linewidth with the appearance of a coherent peak for signals with a low frequency noise power spectral density (FN-PSD) approaching the B-separation line. This is important to achieve a tight phase-lock, e.g., for frequency comb stabilization. We studied this transition both experimentally and by simulations using different types of frequency noise spectra. The integrated phase noise ΔØrms is shown to be the relevant parameter for the occurrence of a coherent peak, which can be achieved even for values higher than 1-rad and if the FN-PSD exceeds the B-separation line.

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**Robustness Testing of a Compact Auxiliary Laser for an Optical Atomic Clock Under Space Conditions** **#1223#**

Bastian Eder{3}, André Kulosa{2}, Stéphane Schilt{4}, Laurent Balet{1}, Steve Lecomte{1}, Martin Hutterer{3}, Laura Pedrosa Rodríguez{3}, David Parker{5}, Yeshpal Singh{5}, Kai Bongs{5}, Ernst Rasel{2}
{1}CSEM, Switzerland; {2}Leibniz Universität Hannover, Germany; {3}OHB Systems AG, Germany; {4}Université de Neuchatel, Switzerland; {5}University of Birmingham, United Kingdom

We present robustness tests of a compact external cavity diode laser performed as a first step towards the use of this laser technology in a future space optical clock. Operation of the laser in environmental conditions representative of the International Space Station (ISS) have been characterized. Continuous measurements of the laser output power and emission wavelength during thermal-vacuum cycles are presented. Furthermore, the laser survived to gamma and protons irradiations at a total dose corresponding to the cumulated dose simulated for a 2-year mission on the ISS, with no significant change of its performance, such as threshold current and slope efficiency.

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**Development of a Strontium Optical Lattice Clock for the SOC Mission on the ISS** **#1231#**

Sruthi Viswam{9}, Lyndsie Smith{9}, Stefano Origlia{1}, Wei He{9}, Dariusz Sweirad{9}, Josh Hughes{9}, Ole Kock{9}, Yeshpal Singh{9}, Kai Bongs{9}, Soroosh Alighanbari{1}, Stephan Schiller{1}, Stefan Vogt{6}, Uwe Sterr{6}, Christian Lisdat{6}, Rudolphe Le Targat{5}, Jèrôme Lodewyck{5}, David Holleville{5}, Bertrand Venon{5}, Sébastien Bize{5}, Geoffrey P Barwood{3}, Patrick Gill{4}, Ian Hill{4}, Yuri

B Ovchinnikov{4}, Nicola Poli{8}, Guglielmo Tino{8}, Jürgen Stuhler{7}, Wilhelm Kaenders{7}, Ernst Rasel{2}
{1}Heinrich- Heine-Universität Düsseldorf, Germany; {2}Leibniz Universität Hannover, Germany; {3}National Physical Laboratory, United Kingdom; {4}National Physical Laboratory Teddington, United Kingdom; {5}Observatoire de Paris, France; {6}Physikalisch-Technische-Bundesanstalt, Germany; {7}TOPTICA Photonics AG, Germany; {8}Universita di Firenze, Italy; {9}University of Birmingham, United Kingdom

Transportable optical lattice clock targetted for space applications.

| A3L-A | Lattice Clocks I | P/X001 |
|---|---|---|
| Chair | Ekkehard Peik | |

**16:00 Yb Optical Lattice Clock with 10^-18-Level Standard Uncertainty #1103#**

Tai Hyun Yoon, Nathan Hinkley, William McGrew, Marco Schioppo, Roger Brown, Kyle Beloy, Robert Fasano, Nathaniel Phillips, Jeffery Sherman, Christopher Oates, Andrew Ludlow
NIST, Time and Frequency Division, United States

Recently, optical lattice clocks have demonstrated fractional instability at the $10^{-18}$ level. Here, we report efforts for improving stability of the NIST Yb optical lattice clock with ≤ 1 × 10^(-16)/√τ level, for averaging time in seconds. Furthermore, we provide an update on recent work extending the systematic uncertainty evaluation to the 10^(-18) level. We have carried out a detailed investigation into residual Doppler shifts which could otherwise compromise accuracy of a lattice clock. Additionally, we describe optical lattice tunneling considerations, and recently implemented sideband cooling mechanisms yielding axial atomic temperatures < 1 uK, which can significantly suppress tunneling frequency shifts. We also highlight detailed studies of Stark shifts due to the optical lattice, yielding a precise characterization of lattice polarizability, hyperpolarizability, vector Stark, and M1/E2 contributions. In addition, we have improved measurements of the probe AC Stark shift and second-order Zeeman shift, and report our current total systematic uncertainty in the low 10^(-18) level.

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**16:20 A Magnesium Optical Lattice Clock #1129#**

Tai Hyun Yoon, Nathan Hinkley, William McGrew, Marco Schioppo, Roger Brown, Kyle Beloy, Robert Fasano, Nathaniel Phillips, Jeffery Sherman, Christopher Oates, Andrew Ludlow
NIST, Time and Frequency Division, United States

We report on the progress towards a highly-accurate optical lattice clock with bosonic 24Mg. Recently, we measured the frequency of the magnetically enhanced 1S0 " 3P0 clock transition at 458 nm to be 655 058 646 691(101) kHz and determined its magic wavelength of 468.46(21) nm. The quadratic Zeeman shift of the clock transition was found to be -206.6(2.0) MHz/T2. All values are in agreement with previous calculations.

### 16:40 Comparison of a Mercury Optical Lattice Clock with Primary and Secondary Frequency Standards #1162#

Maxime Favier, Rinat Tyumenev, Slawomir Bilicki, Eva Bookjans, Daniele Nicolodi, Michel Abgrall, Jocelyne Guéna, Yann Le Coq, Rodolphe Le Targat, Jerome Lodewyck, Luigi De-Sarlo, Sebastien Bize
SYRTE, France

We will also present an absolute frequency measurement of the mercury clock transition, obtained by comparing the Hg optical lattice clock with the atomic fountain FO2-Cs at SYRTE. This measurement has an uncertainty of 4.3x10-16, close to the limit imposed by atomic fountains and, to our knowledge, the best uncertainty to date for the direct measure-ment of Hg vs Cs. Furthermore, we will report on the first direct determination of the fre-quency ratio between neutral mercury and Rb obtained through comparison with the atomic fountain FO2-Rb, as well as a direct optical to optical comparison of the mercury and strontium optical lattice clocks at SYRTE. The value of the Hg/Sr frequency ratio that we obtain as an uncertainty of 1.8x10-16 limited by Hg and is in good agreement with the value reported by RIKEN/UT. This is to our knowledge the only frequency ratio that was measured by two independent groups with an uncertainty beyond that of the SI second. These kinds of comparisons are relevant for tests of the variation of fundamental constants, as well as for assessing the reliability of optical frequency standards in view of a redefinition of the SI second.

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### 17:00 Operational Strontium Optical Lattice Clocks #1222#

Jérôme Lodewyck, Slawomir Bilicki, Eva Bookjans, Grégoire Vallet, Rodolphe Le Targat
LNE-SYRTE, France

We demonstrate that an optical lattice clock with strontium atoms can by reliably operated over time periods of several weeks, with a time coverage larger than 80%. These performances are compatible with the realization of robust time scales with optical clocks. We take advantage of these long integration times to report repeated and consistent comparisons of one of our strontium clocks with two atomic fountains with a statistical uncertainty below 10^−16.

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### 17:20 Higher-Order and Non-Linear Effects on Precision of Clocks of Neutral Atoms in Optical Lattices #1225#

Vitaly Ovsiannikov{3}, Sergey Marmo{3}, Vitaly Palchikov{1}, Hidetochi Katori{2}
{1}FGUP VNIIFTRI, Russia; {2}University of Tokyo, Japan; {3}Voronezh State University, Russia

The results of numerical evaluations presented in this paper determine fundamental re-strictions to various strategies of reducing uncertainties on optical lattice clocks of the groupII atoms. Detailed considerations of the use of strictly forbidden transition 3P0 → 1S0 for the time and frequency standard indicate possible methods of eliminating or accounting for the multi-polar and higher-order dipole shifts of the clock levels. In particular, the difference between spatial distributions of electric-dipole (E1) and multipolar (M1 and E2)

atom-lattice interac-tion is presented explicitly for an attractive red-detuned lattice. The case of repulsive blue-detuned lattice for Sr atoms is also considered in the paper.

| **A3L-B** | **Space Applications** | **P/L001** |
|---|---|---|
| **Chair** | **Marco Belloni** | |

**16:00 Data Timing and Clock Monitoring in the Gaia Astrometric Mission#1155#**

(Invited paper) Sergei Klioner
Technische Universitaet Dresden, Germany

Gaia is an ESA space mission with the main goal to provide astrometric and spectro-photometric measurements of over one billion celestial objects. The accuracy of astrometric parameters should reach the level of about 10 microarcseconds. This level of accuracy requires in particular high-accuracy timing information for the observational data. To meet this requirement the spacecraft has a Rubidium clock, for which a special one-way time synchronization is organized. The presentation will review all ingredients of the data timing and clock monitoring process used in Gaia.

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**16:40 Impact of Turbulence on High Precision Ground-Satellite Frequency Transfer with Two-Way Coherent Optical Links #1160#**

Clélia Robert{1}, Jean-Marc Conan{1}, Peter Wolf{2}
{1}ONERA, the French Aerospace Lab, F-92322 Châtillon, France, France; {2}SYRTE, Observatoire de Paris, CNRS, LNE, France

We provide statistics on heterodyne efficiency for different turbulence strengths and system parameters. We show that to avoid large fluctuations in signal to noise ratio with frequent extinctions we need to correct at least for tip-tilt. Second, we present examples of temporal phase noise evolution for both up and downlink. Finally, we quantify the two-way partial compensation of the phase noise and its impact on the frequency stability of space to ground clock comparisons in terms of Allan variance.

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**17:00 Optical Two-Way Timing System for Space Geodesy Applications #1079#**

Jan Kodet{4}, Ulrich Schreiber{4}, Petr Panek{1}, Ivan Prochazka{2}, Benjamin Männel{3}
{1}Academy of Sciences of the Czech Republic, Institute of Photonics and Electronics, Czech Rep.; {2}Czech Technical University in Prague, Czech Rep.; {3}ETH Zurich, Zurich, Switzerland; {4}Technische Universität München, Germany

Until now time itself is not an observable in space geodesy. The major reason for this fact is the considerable difficulty to keep track of the phase of the clock oscillation between the point of origin and the point of the measurement. However, if geodesy will attempt to provide a reference frame fully based on general relativity, a proper treatment of time is mandatory. The Geodetic Observatory Wettzell is currently in the process to modernize the timing system such that the phase of the master clock can be established at all times. The ultrashort pulses of an optical frequency comb are transporting both time and frequency from the master clock of the observatory to the individual space geodetic techniques, namely Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Navigation Satellite System (GNSS), using a two-way approach, which is in the literature known as the Einstein Synchronization.

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**17:20 Deep Space Navigation Using X-Ray Pulsar Timing with a High Performance Space Atomic Clock #1188#**

Setnam Shemar{2}, George Fraser{3}, Lucy Heil{1}, David Hindley{2}, Adrian Martindale{3}, Philippa Molyneux{3}, John Pye{3}, Robert Warwick{3}, Andrew Lamb{2}

{1}Anton Pannekoek Institute for Astronomy, University of Amsterdam, Netherlands; {2}National Physical Laboratory, United Kingdom; {3}University of Leicester, United Kingdom

We describe a recent study for ESA on the feasibility of deep space navigation using X-ray pulsar timing. The potential technique would allow increased spacecraft autonomy and improved position accuracies in certain scenarios. Simulations of navigation errors based on possible X-ray instrumentation show that the pulsar PSR B1937+21 has the potential to allow a positioning accuracy of order 2 km in the direction of the pulsar, for ranges up to 30 AU. This could be achieved autonomously on the spacecraft using a ~10 hour observation of the pulsar by the X-ray instrument together with a high performance atomic clock.

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|---|---|---|
| **A3L-C** | **Sensors** | **P/L002** |
| **Chair** | **Svenja Knappe** | |

**16:00 Using GaN for MEMS: from Material to Resonators and Sensors #1096#**
(Invited paper)

Marc Faucher{2}, Paul Leclaire{2}, Christophe Morelle{2}, Isabelle Roch{2}, Bertrand Grimbert{2}, Eric Frayssinet{1}, Virginie Brandli{2}, Lionel Buchaillot{2}, Didier Theron{2}, Yvon Cordier{1}

{1}CNRS CRHEA, France; {2}CNRS IEMN, France

We will present an overview of our work toward high performance MEMS resonators and sensors. First, we will show that developing specific epitaxial growth enables MEMS designer to go beyond the current limitations of commercially available material. In particular, we were able to demonstrate ultrathin buffers under 1µm thickness where the AlGaN/GaN heterostructure properties, Young modulus, and careful tuning of stress distribution are validated for device processing. We will report on our design and process of resonators with integrated transducers on these epilayers. The study of piezoelectric actuation, 2DEGs piezo-amplified detection in 3 terminal or 2 terminal tranducers will be described and in particular the understanding of frequency variations upon bias conditions. In conclusion, we will assess the capability of GaN for MEMS accelerometers operating with wide range and resolution under 5mg/Hz1/2.

**16:40 Stability and Durability of Resonant SAW Strain Sensors #1016#**

Victor Kalinin, Arthur Leigh, Alexander Stopps
Transense Technologies plc, United Kingdom

Resonant SAW strain sensing elements used in non-contact torque, force and vibration sensors are investigated from the point of view of their stability and durability. Results of fatigue testing of the SAW sensing elements bonded to metal shafts with a stiff adhesive are presented. They demonstrate the sensor durability and stability of the strain sensitivity up to 13 million strain cycles. Stability of the frequency of the SAW differential resonant sensing elements is also investigated showing the sensor zero drift of approximately 0.14…0.62% FS per year at 90°C.

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**17:00 Experimental Procedure to Design Stressed HBAR Devices When the Third-Order Elastic Constants Are Not Known #1114#**

Thomas Baron{2}, Ludovic Bebon{2}, Valérie Petrini{2}, Gilles Martin{2}, Jean-Marc Lesage{1}
{1}DGA, France; {2}FEMTO-ST, France

Third-order elastic constants are mandatory requirements to compute stress sensitivity. Experimental procedure to design stressed devices when the third-order elastic constants are not known are described. We use HBAR based on LiNbO3 (YXl)/163 piezoelectric layer on LiTaO3 Z-cut substrate as example of this approach. Vibration sensitivity of HBAR oscillators are measured for different package configurations. These configurations allow the computation of the six stress sensitivity coefficients of HBAR. So, an oscillator and a pressure sensor design optimization can be done although the involved nonlinear elastic constants have not been determined yet.

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**17:20 S0 Lamb Wave Resonators for in-Liquid Sensing: Promising Alternative to Shear Bulk Acoustic Wave Devices #1125#**

Teona Mirea{2}, Ventsislav Yantchev{1}, Enrique Iborra{2}
{1}Chalmers University of Technology and Q-Arts Consulting Ltd, Bulgaria;
{2}Universidad Politécnica de Madrid, Spain

S0 Lamb wave resonators (S0-LWR) have shown great potential for in-liquid operation. They can be used on a dual quantity sensor platform since they are sensitive to both, mechanical (density and viscosity) and electrical (dielectric permittivity) properties of the liquid. Here we present extensive theoretical and experimental studies on their in-liquid sensing mechanisms. Additionally, we compare them to the commonly used solidly mounted shear mode bulk acoustic wave devices and show their comparable in-liquid performance. This places S0-LWR as promising alternative with the advantage of using commercial c-oriented AlN deposition.

# Wednesday 6th April

| | P/X001 | P/L001 | P/L002 |
|---|---|---|---|
| 8.40-10.00<br><br>10.00-10.40 | B1L-A<br>**Quantum Measurement**<br>Chr: Patrick Gill<br>Track: Optical Frequency Standards and Applications<br><br>**Exhibitors presentations**<br>Chr:Wolfgang Schaefer | B1L-B<br>**GNSS and Applications**<br>Chr: Per Olof Hedekvist<br>Track: Timekeeping, Time and Frequency Transfer, GNSS Applications | B1L-C<br>**Cross Correlation**<br>Chr: Claudio Calosso<br>Track: Oscillators, Synthesizers, Noise, & Circuit Techniques |
| 10.40 | Coffee / tea break | | |
| 11:10-12.30 | B2L-A<br>**Applications of Optical Frequency Standards**<br>Chr: Philip Tuckey<br>Track: Optical Frequency Standards and Applications | B2L-B<br>**Atomic Magnetometers and Their Applications**<br>Chr: Gaetano Mileti<br>Track: Microwave Frequency Standards | B2L-C<br>**Advances in TWSTFT**<br>Chr: Miho Fujieda<br>Track: Timekeeping, Time and Frequency Transfer, GNSS Applications |
| 12.30 | Lunch | | |
| 14.00-15.40 | Poster session 2 | | |
| 15.40 | Coffee / tea break | | |
| 16:00-17.40 | B4L-A<br>**Ion Clocks**<br>Chr: Tai Hyun Yoon<br>Track: Optical Frequency Standards and Applications | B4L-B<br>**Timing Networks and Applications**<br>Chr: Patrizia Tavella<br>Track: Timekeeping, Time and Frequency Transfer, GNSS Applications | B4L-C<br>**Atom Interferometers**<br>Chr: Arnaud Landragin<br>Track: Microwave Frequency Standards |

Dinner at National Railway Museum 19.00 – 23.00 coaches depart from outside exhibition centre 18.30.

**B1L-A Quantum Measurement P/X001**
**Chair Patrick Gill**

### 08:40 Hofstadter Optical Lattice for Ultracold Ytterbium Atoms (Invited) #1157#

(Invited) Fabrice Gerbier, Quentin Beaufils, Jérôme Beugnon, Manel Bosch Aguilera, Raphaël Bouganne, Alexandre Dareau, Daniel Döring, Matthias Scholl
LKB, France

This talk will describe new experiments probing and manipulating many-body properties of ultracold quantum gases using ultra-narrow “clock” transitions. I will focus on our experimental project, which aims at engineering a special kind of optical lattice realizing an effective magnetic field coupling to the atomic motion - the Hofstadter optical lattice. Our specific experimental scheme uses an ultra-narrow optical transition linking the ground state to a metastable excited state in bosonic Ytterbium. (also used as ``clock'' transition in Yb-based optical atomic clocks). I will present the current status of the experiment, including spectroscopy of Bose-Einstein condensates (BEC) on the clock transition, and the observation of coherent Rabi oscillations between a BEC in the ground state and in the excited state.

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### 09:20 Atomic Quadrupole Moment Measurement Using Dynamic Decoupling #1158#

Ravid Shaniv, Nitzan Akerman, Roee Ozeri
The Weizmann Institute, Israel

We present a method that uses dynamic decoupling of a multi-level quantum probe " a single 88Sr+ ion " in order to measure electric quadrupole energy shift in the D_(5/2) level. In contrast with typical two-level dynamic decoupling schemes, here we take advantage of the six-fold D_(5/2) Zeeman manifold of equidistant levels and reduce the effect of magnetic field noise. By using our measurement scheme, we were able to measure the quadrupole moment of the D_(5/2) level in 88Sr+ with precision better than that of the previous measurement by an order of magnitude.

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### 09:40 Quantum Logic State Detection for Molecular Ions #1027#

Fabian Wolf{1}, Yong Wan{1}, Jan Heip{1}, Florian Gebert{1}, Chunyan Shi{1}, Piet Schmidt{2}
{1}Physikalisch-Technische Bundesanstalt, Germany; {2}Physikalisch-Technische Bundesanstalt, Universität Hannover, Germany

Molecules offer fascinating possibilities for fundamental research due to their rich internal structure. The lack of a cycling transition for cooling and detection in most molecules has limited wide-spread applications. While the development of quantum logic techniques for atomic ions has enabled spectroscopy of previously inaccessible species, the application of these techniques to molecular ions is still infeasible. Here, we present the first implementation of non-destructive state detection using quantum logic operations between a molecular and an atomic ion. This result establishes a technique enabling quantum

information processing and high-precision spectroscopy for tests of fun-damental physics with cold molecular ions.

| B1L-B | GNSS and Applications | P/L001 |
|---|---|---|
| Chair | Per Olof Hedekvist | |

**08:40 Towards Operational Sub 10^-16 Frequency Transfer with IPPP #1040#**

Gerard Petit{1}, Sylvain Loyer{2}, Felix Perosanz{3}
{1}BIPM, France; {2}CLS, France; {3}CNES, France

Precise Point Positioning (PPP) is the technique of choice for GPS time and frequency transfer, with a typical uncertainty for frequency comparisons of order 1x10-15 at 1-day aver-aging and a few 10-16 at 5 to 10 day averaging. One approach to overcome the limitations of "classical PPP" is to consider the integer nature of phase ambiguities and the CNES-GRGS group has been a pioneer in applying integer ambiguity resolution to PPP. We show that this IPPP technique reaches a frequency transfer accuracy of 1x10-16 at ~3 to 5-day averaging for regional links. We present steps taken towards the operational use of IPPP along with some recent results.

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**09:00 Highly Dynamic Distance Measurement for GNSS Using the Frequency Domain Distance Measurement, for Time and Frequency Transfer #1140#**

Bastian Eder{2}, Martin Hutterer{1}, Thomas Unterholzer{1}, Sebastian Lindner{2}, Andreas Fischer{1}, Philipp Putzer{1}, Sebastian Schweyer{2}, Norbert Lemke{1}, Reinhard Kienberger{2}, Ulrich Schreiber{2}, Urs Hugentobler{2}
{1}OHB System AG, Germany; {2}Technische Universität München, Germany

A new approach of distance measurement promises a very compact, robust, simple and fast application. The Frequency Domain Distance Measurement (FDDM) is hereby not only for absolute distance measurements, but for highly dynamic measurements as well. This system is capable of measuring static systems as well as highly dynamic systems with speeds > 10 km/sec, and velocity resolution < 1 cm/sec. The combination of FDDM and a balanced optical cross correlation promises time and frequency transfer between largest distances with stabilities better than optical clock performances, which can be used for future Global Navigation Satellite System scenarios.

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**09:20 Performance of the NeQuick G Iono Model for Single-Frequency GNSS Timing Applications #1032#**

Ricardo Píriz{1}, Pedro Roldán{1}, Rafal Golcz{1}, Carlos Moriana{1}, Andreas Bauch{2}, Julia Leute{2}
{1}GMV, Spain; {2}PTB, Germany

GNSS timing is currently used worldwide in critical real-time systems that require precise synchronisation or time-stamping at geographically dispersed sites. For applications where multiple timing equipment needs to be deployed, it is desirable to use low-cost (normally single-frequency) receivers. GPS provides the simple, low-accuracy Klobuchar ionospheric model. For Galileo, the Euro-pean Union has recently published a detailed description and implementation guidelines for the NeQuick G user model [1]. In this paper we analyse the single-frequency timing accuracy using the NeQuick G model. The study is based on data from two GNSS receivers, located at PTB and connected to the highly stable UTC(PTB) timescale.

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**09:40 Experimental Time Dissemination Services Based on European GNSS Signals: the H2020 DEMETRA Project #1151#**

Patrizia Tavella
Istituto Nazionale di Ricerca Metrologica, Italy

The DEMETRA project, funded by the European Union in the frame of the Horizon 2020 program, aims at developing and experimenting time dissemination services based on the European GNSS, adding particular features like certification, calibration, or integrity, that could be of interest to a wide range of users as traffic control, energy distribution, finance, telecommunication, and scientific institutions. The project has a 6 month experimentation campaign starting next March 2016 and the paper will report the first results showing potentialities and limits of the proposed time dissemination services, aiming to foster the exploitation of the European GNSS for timing applications.

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| **B1L-C** | **Cross Correlation** | **P/L002** |
| **Chair** | **Claudio Calosso** | |

**08:40 A 1 MHz to 50 GHz Direct Down-Conversion Phase Noise Analyzer with Cross Correlation #1012#**

Gregor Feldhaus, Alexander Roth
Rohde & Schwarz, Germany

A new instrument for phase noise test covers a frequency range from 1 MHz up to 50 GHz with direct down-conversion analog I/Q mixers and sampling of the baseband signal. The traditional PLL is replaced by a digital FM demodulator as a phase detector and for frequency tracking. An additional AM demodulator enables concurrent measurement of phase noise and amplitude noise. Phase noise as low as -183 dBc/Hz at 100 MHz carrier frequency and 10 kHz offset can be measured within two minutes.

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**09:00 Cross-Spectral Collapse from Anti-Correlated Thermal Noise in Power Splitters #1051#**

Craig Nelson, Archita Hati, Dave A. Howe
National Institute of Standards and Technology, United States

We discuss the effect of anti-correlated thermal noise of various reactive and resistive power splitters on the cross-spectrum phase noise measurement of thermally-limited oscillators.

**09:20 On a Conceptual Error in Cross Spectrum PM Noise Measurements#1056#**

Yannick Gruson{1}, Vincent Giordano{1}, Ulrich L. Rohde{2}, Enrico Rubiola{1}
{1}CNRS Femto-ST Institute, France; {2}Synergy Microwave Corporation, United States

Modern instruments use two equal channels and cross PSD to average out the single-channel background. The loss-free power splitter at the input is actually a directional coupler. We learn from thermometry that the cross PSD is k(Tc-Td), where kTc and kTd are the thermal energy of the oscillator and of the dark port. The latter is generally not accounted for, which results a systematic error. We provide the formal derivation, and the experimental evidence using an audio-frequency mockup. This choice is for full control on crosstalk. Our measurement are done in a Faraday cage with additional magnetic shielding.

**09:40 Memory-Efficient High-Speed Algorithm for Multi-Tau PDEV Analysis #1141#**

Magnus Danielson{2}, François Vernotte{3}, Enrico Rubiola{1}
{1}CNRS FEMTO-ST Institute, Dept Time and Frequency, France; {2}Net Insight AB, Sweden; {3}Observatory THETA/UTINAM, UBFC/UFC and CNRS, France

The Omega counter was introduced to improve phase noise rejection by using a least square algorithm. The associated variance is the PVAR which is more efficient than MVAR to separate the different noise types. However, unlike AVAR and MVAR, the decimation of PVAR estimates for multi-tau analysis is not possible if each counter measurement is a single scalar. This paper gives a decimation rule based on two scalars, the processing blocks, for each measurement. For the Omega-counters, this implies the definition of an output standard as well as hardware requirements for performing high-speed computations of the blocks.

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| **B2L-A** | **Applications of Optical Frequency Standards** | **P/X001** |
| **Chair** | **Philip Tuckey** | |

**11:10 Cold Highly Charged Ions for Highest Precision Spectroscopy #1198#**
(Invited paper)

Lisa Schmöger{4}, Oscar Versolato{4}, Maria Schwarz{4}, Matthias Kohnen{5}, Alexander Windberger{3}, Baptist Piest{3}, Stefanie Feuchtenbeiner{3}, Jofre Pedregosa{2}, Tobias Leopold{5}, Peter Micke{4}, Anders Hansen{1}, Thomas Baumann{3}, Michael Drewsen{1}, Thomas Pfeifer{3}, Joachim Ullrich{5}, Piet Schmidt{5}, José Crespo López-Urrutia{3}
{1}Aarhus University, Denmark; {2}Aix-Marseille University, France; {3}Max-Planck-Institut für Kernphysi, Germany; {4}Max-Planck-Institut für Kernphysik / Physikalisch-Technische Bundesanstalt, Germany; {5}Physikalisch-Technische Bundesanstalt, Germany

Cold, strongly localized highly charged ions (HCIs) are of particular interest for frequency metrology (development of novel optical clocks) and the search for physics beyond the Standard Model. We have successfully Coulomb crystallized highly-charged Ar13+ ions in a

cryogenic Paul trap through sympathetic cooling with co-trapped, continuously laser-cooled Be+ ions. This constitutes a significant step forward for high-precision spectroscopy of HCIs.

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**11:50 Frequency Combs for Astronomical Precision Spectroscopy #1228#**

Rafael Probst{2}, Yuanjie Wu{2}, Tilo Steinmetz{1}, Sebastian Stark{1}, Theodor Hänsch{2}, Thomas Udem{2}, Ronald Holzwarth{1}
{1}Menlo Systems GmbH, Germany; {2}MPI für Quantenoptik, Germany

In recent years, laser frequency combs (LFCs) have found their way from precision laboratory spectroscopy into astronomy, as calibrators for astronomical spectrographs. Here we present a frequency combs with a flat spectrum covering most of the visible part of the optical spectrum with a 25 GHz mode spacing, perfectly suited for the calibration of astronomical spectrographs.

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**12:10 Searching for Dark Matter with Atomic Clocks and Laser Interferometry #1062#**

Yevgeny Stadnik, Victor Flambaum
University of New South Wales, Australia

We propose new schemes for the direct detection of low-mass bosonic dark matter, which forms an oscillating classical field, using atomic clocks and laser interferometers. We have recently shown that such dark matter can induce both a ‘slow’ cosmological evolution and oscillating variations in the fundamental constants. Oscillating variations in the fundamental constants produce oscillating shifts in the transition frequencies of atomic clocks and other atomic systems. Using recent atomic dysprosium spectroscopy data, we have derived limits on the quadratic interaction of dark matter with the photon that improve on existing constraints by up to 15 orders of magnitude.

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| **B2L-B** | **Atomic Magnetometers and Their Applications** | **P/L001** |
| **Chair** | **Gaetano Mileti** | |

**11:10 Precision Measurements and Navigation with Frequency Measurements at the pHz Level (Invited) #1237#**

Michael Romalis
Princeton University, United States

In this talk I will describe recent progress in using polarized nuclear spins for precision tests of fundamental physics as well as for practical applications, such as inertial rotation sensing. Nuclear spin polarized gases have particularly long spin coherence times, allowing for frequency measurements with precision down to the pHz level.

**11:50 Frequency-Tunable Microwave Field Imaging in an Atomic Vapor Cell #1087#**

Andrew Horsley, Philipp Treutlein
University of Basel, Switzerland

We present a frequency tunable atomic vapor cell magnetometer operating at microwave frequencies from GHz to tens of GHz, a four orders of magnitude extension of the frequency tunable range of atomic magnetometers. Potential applications include near-field characterisation of microwave circuitry and devices, and medical microwave sensing and imaging.

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**12:10 Dual Frequency Spin-Polarized Pumping #1083#**

Dmitri L. Boiko
CSEM, Switzerland

Progress towards efficient and stable spin-polarized pumping for chip-scale atomic magnetometers and gyroscopes is reported. Typically, such devices utilize moderate pressure Rb cells containing several hundred torr of Xe and N2 buffer that yield strong overlap of hyperfine absorption lines in Rb. Nevertheless we find that magnetic precession reveals large sensitivity to the pump-probe laser frequency. To overcome it, a dual frequency (DF) spin-polarized optical pumping for reduction of the laser frequency sensitivity is proposed. In addition, DF interrogation narrows the width of magnetic resonance and reduces bias.

**B2L-C Advances in TWSTFT P/L002**
**Chair Miho Fujieda**

**11:10 Remote Optical and Fountain Clock Comparison Using Broadband TWSTFT and GPS PPP #1136#**

Franziska Riedel
Physikalisch-Technische Bundesanstalt, Germany

Various Yb ion, Sr lattice and Cs fountain clocks at INRiM, LNE-SYRTE, NPL and PTB had been compared simultaneously over a 3-week campaign using satellite-based techniques. With full 20 MChip/s modulation bandwidth TWSTFT links and PPP/iPPP analysis of GPS link data, instabilities of a few 1E-16 could be achieved for both techniques. For the calculation of the clock-to-clock ratios and their uncertainties, gap-tolerant weighted averaging with different optimized weighting functions was employed.

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**11:30 A Study on Reducing the Diurnal in the Europe-to-Europe TWSTFT Links #1098#**

Victor Zhang, Thomas Parker, Shengkang Zhang
NIST, United States

In this study, we report that the diurnal in the Europe-to-Europe TWSTFT links can be reduced by using the triangle difference of the transatlantic TWSTFT differences. Notice that the triangle difference also reduces the short-term transfer noise observed in the direct difference. We will examine the triangle difference for several Europe-to-Europe links and analyze where the improvement comes from.

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### 11:50 The 2015 TWSTFT Calibration for UTC and Related Time Links #1047#

Zhiheng Jiang{1}, Dirk Piester{4}, Christian Schlunegger{2}, Erik Dierikx{7}, Victor Zhang{3}, Javier Galindo{5}, Jonathan Hirschauer{6}, Demetrios Matsakis{6}
{1}BIPM, France; {2}METAS, Switzerland; {3}NIST, United States; {4}PTB, Germany; {5}ROA, Spain; {6}USNO, United States; {7}VSL, Netherlands

TWSTFT is one of the primary time transfer techniques for UTC generation. Calibration is one of its key strengths, but it requires considerable investment in staffing, time, and funding. As a practical matter, only the UTC links need to be calibrated. Some laboratories make use of TW time comparisons for applications other than UTC computation and the Triangle Closure Calibration (TCC) technique is used for the calibration.

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### 12:10 TWSTFT Results by Using Software-Defined Receiver Data #1024#

Yi-Jiun Huang{3}, Wen-Hung Tseng{3}, Shinn-Yan Lin{3}, Sung-Hoon Yang{1}, Miho Fujieda{2}
{1}Korea Research Institute of Standards and Science, Korea, South; {2}National Institute of Information and Communications Technology, Japan; {3}Telecommunication Laboratories, Chunghwa Telecom, Taiwan

The accuracy of TWSTFT is currently limited due to instabilities of signal arrival time. We use a software-defined receiver (SDR) to accurately measure the arrival time of code signal transmitted by SATRE modem, and then we found it exhibits the capacity against the TWSTFT diurnal variations. The SDR systems have been successfully installed at TL, NICT and KRISS since 2015. For data of the KRISS-TL link, the TDEV plot of SATRE modem shows a peak of 134 ps at 8 hours, where the TDEV of SDR is only 32 ps.

## B3P-E Oscillators and Synthesizers — Poster Area

**Chair** Jean-Pierre Aubry

### An Ultra Stable Oscillator for the 3GM Experiment of the Juice Mission #1021#

Aviv Shapira, Avinoam Stern, Shemi Prazot, Ronny Mann, Yefim Barash, Edoardo Detoma, Benny Levy
AccuBeat LTD, Israel

An Ultra Stable Oscillator (USO) is being developed by AccuBeat for the 3GM radio occultation experiment of the ESA JUICE mission. The USO, 15x13x10cm3, will provide a highly stable reference signal for the one way (space to ground) radio link to investigate the structure of the neutral atmospheres and ionospheres of Jupiter and its moons. A partial engineering model of the USO (PEM) was built and tested in thermal vacuum. It has demonstrated a frequency stability below 2E-13 for a 5MHz output, at an averaging time 1s to 1000s, thus meeting the requirements for technology readiness level 5 (TRL5).

**High Performance Miniature Integrated OCXO Solution** **#1118#**

Karl Ward
Rakon UK Ltd, United Kingdom

Traditional OCXO devices have been around for many years offering frequency stabilities superior to those of smaller, lower power TCXO devices. In today's world where size constraints and power conscious systems require exacting performance, this paper presents a unique solution that addresses these challenges. Based upon a TCOCXO topology, the single chip (ASIC) solution described requires only a crystal and optional capacitors to meet frequency versus temperature stabilities down to ±2ppb over -40/85ºC with an oven size of only 5x3.2 mm.

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**Long-Term Frequency Stability Improvement of OCXO Using CSAC** **#1191#**

Tomáš Bagala{1}, Adam Fibich{1}, Vladimír Stofanik{2}
{1}FEEI SUT Bratislava, Slovakia; {2}FEEI SUT Bratislava, IP SAS Bratislava, Slovakia

Our attention is dedicated to ways of stabilizing the frequency of the OCXO using CSAC module. From our research will be proposed stabilization system using two mentioned oscillator with guaranteed properties in the long term frequency stability of output signals that will have lower phase noise, than origin CSAC module.

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**Theory of VCO Phase Noise Reduction Using Parallel Varactor Diodes** **#1226#**

Michael Underhill
Underhill Research Limited, United Kingdom

Significant noise reduction has been observed by Rohde and Poddar using several parallel varactor or capacitor switching diodes in a Voltage Controlled Oscillator (VCO) in place of single larger diodes. We theorize that the noise is correlated over the area of a single semi-conductor diode by electromagnetic coupling, whereas the noise from discrete diodes is not correlated. For n equal discrete diodes the maximum reduction is n times. We investigate whether the effective noise temperature of the combined diode resistance has been reduced, or whether the Q has actually been increased, when applied in a Leeson oscillator model.

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| **B3P-F** | **Sensors & Transducers** | **Poster Area** |
| **Chair** | **Svenja Knappe** | |

**Quartz Orientations for Optimal Power Efficiency in Wireless SAW Temperature Sensors** **#1173#**

Alexander Shvetsov{2}, Sergei Zhgoon{2}, Ivan Antcev{1}, Sergei Bogoslovsky{1}, Gennadiy Sapozhnikov{1}
{1}JSC "Radar mms", Russia; {2}National Research University MPEI, Russia

The present work is dedicated to a detailed discussion of the relation between the required value of K2 and the maximum available TCF difference on separate substrates as well as on a single substrate. Orientations with maximum difference of TCF are described for different

requirements to the K2 level. Selected orientations have been studied experimentally and the comparison of calculated and measured results is given.

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**Influence of Induced Stress on AlN-Solidly Mounted Resonators #1201#**

Alvaro Delicado, Marta Clement, Teona Mirea, Bárbara Díaz-Durán, Jimena Olivares, Enrique Iborra
Universidad Politécnica de Madrid, Spain

The frequency response of AlN-based solidly mounted resonators built on rectangular silicon strips silicon is assessed as a function of the mechanical deformation exerted on the substrates, which is assessed with a strain gauge glued on their surface. The electrical behaviour of the resonators is also assessed under DC-polarisation to investigate the influence of the different materials apart from the AlN layer. Simulations of the deformation enable to assess the non-uniform stress in the silicon strip. It is found that longitudinal modes shift to lower frequencies whereas shear modes shift to higher frequencies as the silicon strip is strained.

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**Stress-Sensitivity of Wafer-Level Packaged SAW Delay Lines #1137#**

Lilia Arapan, Guillaume Wong, Bernard Dulmet, Thomas Baron, Jean-Michel Friedt, Vincent Placet
FEMTO-ST, France

We investigate the stress-sensitivity of Wafer-Level Packaged SAW delay lines aimed to wireless stress sensing.The WLP is achieved by soft polymer in order to favor the level of stresses at the SAW surface. We investigate both theoretically and experimentally the influence of this packaging onto the stress-sensitivity of the delay lines micro-machined on Lithium Niobate substrate.

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**High Coupling Phononic SH-SAW Resonators for in-Liquid Operation #1146#**

Ventsislav Yantchev{2}, Teona Mirea{3}, Enrique Iborra{3}, Aldo Jesorka{1}
{1}Chalmers University of Technology, Sweden; {2}Chalmers University of Technology and Q-Arts Consulting Ltd, Bulgaria; {3}Universidad Politécnica de Madrid, Spain

We present integrated IDT-phononic resonators with X-propagating SH-SAW for in-liquid operation. These devices are built on Y-cut LiNbO3 and provide a wave velocity slower than the bulk modes and the RSAW in the structure, hence being well trapped to the surface with very high Keff2 (12%). The latter together with the high dielectric permittivity of the structure allows non-conductive liquid measurement directly over the IDT. Experimental measurements using ethylene glycol-water mixtures demonstrate very high sensitivity of the antiresonant frequency to the liquids densities and viscosities. Moreover very high Keff2 is still preserved in liquid (11.7% - 13.5 %).

**Planar Angle Metrology: the INRIM - INFN Ring Laser Gyroscope #1207#**

Jacopo Belfi{1}, Nicolo' Beverini{3}, Angela Di Virgilio{1}, Enrico Maccioni{3}, Milena Astrua{2}, Marco Pisani{2}, Marco Santiano{2}
{1}INFN- Sezione di Pisa, Italy; {2}INRIM, Italy; {3}Universita' di Pisa, Italy

In a collaboration between INRIM and INFN, we are building a new kind of laser goniometer with a target accuracy is 10 nrad. The angles are measured counting the fringes generated by interference between the two counter-propagating laser beams in a ring laser (Sagnac effect) when the ring cavity is mounted on a rotating platform. The laser cavity, a square of 0.50 m in side, makes use of the last generation dielectric super-mirrors.

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| **B3P-G** | **Microwave Frequency Standards & Applications II** | **Poster Area** |
| **Chair** | **Stefan Weyers** | |

**2D Mot Vacuum Chamber Based on Zerodur #1004#**

Sin Hyuk Yim{1}, Tae Hyun Kim{1}, Sangkyung Lee{1}, Heesook Roh{1}, Kyu Min Shim{1}, Taeg Yong Kwon{2}, Sang Eon Park{2}, Sang-Bum Lee{2}
{1}ADD, Korea, South; {2}KRISS, Korea, South

We construct a vacuum chamber for 2-dimensional magneto-optical trap (2D MOT)based on Zerodur block for producing slow atomic beam [2]. This atomic beam will be used for cold atom interferometer experiment in near future.

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**The NAC - a Miniature CPT Rubidium Clock #1020#**

Avinoam Stern, Benny Levy, Chagai Levy, Uriel Arad, Yefim Barash, Ronny Mann, Alex Gorelik
AccuBeat LTD, Israel

We report of the design and characterization of a miniaturized rubidium clock based on coherent population trapping (CPT). The paper describes the atomic standard key design and performance characteristics, the size of which is 41x35x22mm3 and its power consumption is 1.2W. The clock has demonstrated a frequency stability (ADEV) of 8·10-12 at 1000s averaging time, and an aging (drift) of 3·10-10 per month.

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**Study of Ion Beam Detection in Cesium Beam Frequency Standard with Feedback Ammeter Circuit #1028#**

Ji Wang, Yinguang Ma, Liangyu Huang, Dapeng Chen, Hongwei Zhu, Pei Ma, Jiang Chen
lanzhou institute of physics, China

The paper describes a new scheme adopting the feedback ammeter circuit to amplify ion beam flux generated by physical package of cesium beam frequency standard with magnetic state selection. The feedback ammeter circuit is classic current to voltage converter circuit. The value of the feedback resistance is 100GΩ. Guard shield is included in the feedback circuit. With the feedback circuit, the ion signal from cesium beam tube with 1.0pA can be amplified to 75mV. The cesium beam tube with feedback circuit is currently locked with frequency standard circuit and short term stability of 2E-13@10000s is achieved.

### Magnetic State Selection Impact on Double Resonance Effect in H-Maser #1029#

Michael Aleynikov
FGUP VNIIFTRI, Russia

It is well known double resonance effect in a hydrogen maser appears in a two-photon process in which the Zeeman sublevels of the hydrogen atom ground state hyperfine structure are involved when applying transverse magnetic field near the Zeeman frequency. In this paper new modified Bloch equations intended for arbitrary state selection system have been obtained and calculated. As a result an analysis of state selection performance impact on double resonance in H-maser is produced.

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### The Raman Laser System for Mach-Zehnder Atom Interferometry #1030#

Nan Li, Kaikai Huang, Xuanhui Lu
Zhejiang University, China

We produced two Raman-laser beams with a frequency offset of 6.834GHz by injection-locking of a master diode-laser to a slave diode-laser. The master laser was phase-modulated at 6.834 GHz with an Electro-Optic Modulator and then injected into the slave laser that was oscillating around one of the side-bands. The relative linewidth of the two lasers was less than 1 Hz. Utilizing these laser beams, we realized the coherent manipulation of atomic wave packets in an Mach-Zehnder type atom interferometry.

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### Improvements of the NPL Primary Frequency Standards System #1034#

Filip Ozimek{2}, Weiliang Chen{1}, Jochen Kronjaeger{2}, Piotr Dunst{3}, Rich Hendricks{2}, Krzysztof Szymaniec{2}
{1}National Institute of Metrology, China; {2}National Physical Laboratory, United Kingdom; {3}Space Research Centre, Astrogeodynamical Observatory, Poland

The system consists of two caesium fountain standards to be fully integrated with the NPL time and frequency infrastructure. We report on upgrades to the mature setup of NPL-CsF2 and on the accuracy evaluation of the new fountain NPL-CsF3. In addition, we show improvement in the signal-to-noise ratio and short-term stability achieved by using a laser based local oscillator. In order to avoid a systematic frequency shift due to possible, micro-radian size, microwave phase transients, which might be synchronous with the fountain cycle we have built a triggered phase analyser based on a commercial lock-in amplifier.

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### Investigation on Porous Materials for Cesium Beam Frequency Standard in Space Environment #1038#

Jun Yang, Dixin Zhang, Jiang Chen, Ji Wang, Liangyu Huang, Hongwei Zhu, Yinguang Ma, Dapeng Cheng, Ning Zheng
Lanzhou Institute of Space Technology and Physics, China

Porous materials inside cesium oven play a significant role in enhancing performance of cesium beam frequency standard, such as working lifetime of cesium beam tube, frequency stability of cesium atomic clock and so on. In this paper (for the sake of high quality of cesium atomic beam) the function characteristic about three kinds of porous materials inside cesium oven were investigated in theories and experiments respectively based on design principle of spill-resistant oven.

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**Recent Advances in Compact Rubidium Frequency Standards at KRISS #1063#**

Hyun-Gue Hong{2}, Sang Eon Park{3}, Sangmin Lee{3}, Myoung-Sun Heo{2}, Sang-Bum Lee{2}, Taeg Yong Kwon{2}, Sin Hyuk Yim{1}, Chang Bok Lee{2}
{1}ADD, Korea, South; {2}KRISS, Korea, South; {3}KRISS/UST, Korea, South

We report on recent advances in the laser-pumped Rb vapor cell clock based on a magnetron-type microwave cavity at KRISS. The stability at the current stage marks 4x10-13 at 1 s and stays 10-13 level for integration time up to 10000 s in the presence of linear drift compensation.

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**Microwave Cavity Characterization for Rubidium Frequency Standards #1101#**

Mohammadreza Gharavipour{2}, Anton E. Ivanov{1}, Christoph Affolderbach{2}, Anja Skrivervik{1}, Gaetano Mileti{2}
{1}Laboratoire d'Électromagnétisme et d'Acoustique (LEMA), École Polytechnique Fédérale de Lausanne, Switzerland; {2}Laboratoire Temps-Fréquence, Institut de Physique, Université de Neuchâtel, Switzerland

We report our studies on the new designed magnetron-type microwave cavity operating in the TE011-like mode, at the rubidium hyperfine ground-state frequency of about 6.835 GHz. The properties of the cavity resonance were studied as a function of cavity temperature. Numeri-cal FEM simulations were performed and compared to the experimental results. They shed light on the influence of different design parameters on temperature-dependent behavior of the cavity.

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**Light-Shift Coefficient in GPS Rubidium Clocks: Estimation Methods Using Lamplight/Frequency Correlations #1133#**

Valerio Formichella{1}, James Camparo{2}, Patrizia Tavella{1}
{1}Istituto Nazionale di Ricerca Metrologica, Italy; {2}The Aerospace Corporation, United States

The frequency of the Rubidium Atomic Frequency Standards (RAFS) flying on GNSS satellites is affected by the light-shift effect, which is a change in clock frequency arising from a change in the RAFS' lamplight. We study this effect in GNSS RAFS by estimating the RAFS' light shift coefficient and its possible variation in time using two different methods: a lamplight-induced frequency jump method, and a lamplight/frequency correlation method. We present analyses using GPS Block IIR clock frequency and lamplight telemetry data, and evaluate the light shift's impact on GNSS by showing the influence of lamplight behavior on RAFS frequency stability.

**Development and Spectral Characterisation of Ridge DFB Laser Diodes for Cs Optical Pumping at 894 nm** **#1145#**

Renaud Matthey{3}, Florian Gruet{3}, Christoph Affolderbach{3}, Nicolas Von Bandel{1}, Michel Garcia{1}, Michel Krakowski{1}, Patrick Berthoud{2}, Gaetano Mileti{3}
{1}III-V Lab, France; {2}Oscilloquartz SA, Switzerland; {3}Université de Neuchâtel, Switzerland

A number of research fields like time and frequency or magnetometry make use of lasers to prepare and interrogate caesium atoms. Distributed-feedback diode (DFB) lasers with sub-MHz linewidth operating at 894 nm at the caesium D1 resonance line are barely available. We report on the development and spectral characterisation of 894-nm DFB lasers with Al-free active region, which demonstrate linewidth between 640 kHz and 1.0 MHz.

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**"Second Order Magic" RF Dressing for Trapped Alkali Atoms** **#1167#**

Georgy Kazakov, Thorsten Schumm
Vienna University of Technology, Austria

Using magnetically trapped ensembles of cold atoms in microwave clocks allows to enhance the interrogation time. To mitigate the perturbing effects of the magnetic trap, "magic field" configurations are employed, where the involved clock transitions becomes independent of the atoms potential energy to first order. Still, higher order effects remains and contribute to dephasing. We propose to add the technique of magic radiofrequency dressing to selectively modify the potential landscape experienced by the two clock states in a static magnetic trap. We demonstrate that weak RF dressing can be used to cancel the relative energy shift between the clock states to both, first and second order with respect to the magnitude of the DC magnetic field in the trap. We identify and characterize these "second-order magic" conditions for 87Rb atoms trapped in a RF-dressed Ioffe-Pritchard-type trap, compare such trap with conventional ones, and characterize the robustness of this second-order-magic potential to deviations of magnitude and polarization of the involved fields.

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**Recent Progress in the Development of a Hydrogen Maser in the TE111 Mode** **#1185#**

Emeline Van der Beken{2}, Daniel Léonard{1}, Arnaud Counet{1}, Thierry Bastin{2}
{1}Gillam-FEi, Belgium; {2}University of Liège, Belgium

We present the recent progress in the development of a hydrogen maser in the unusual TE111 mode. In contrast to standard hydrogen maser that exploits the TE011 mode, the TE111 mode allows one to design hydrogen masers with significant reduced dimensions which represents a huge benefit for space applications and in particular for the global positioning system. We present in details the different parts of our model: cavity with a thin Teflon sheet, magnetic shielding, thermal control of the maser...

**Calculation of Quadratic Zeeman Shift by Regularization Method for an Atomic Fountain Clock KRISS-F1 #1209#**

Young-Ho Park{1}, Sang Eon Park{3}, Myoung-Sun Heo{2}, Taeg Yong Kwon{2}, Hyun-Gue Hong{2}, Sangmin Lee{3}, Sang-Bum Lee{2}
{1}IBS, Korea, South; {2}KRISS, Korea, South; {3}KRISS,UST, Korea, South

We present quadratic Zeeman shift by regularization method for an atomic fountain clock KRISS-F1. We were able to deduce a reasonable field map with an approach of solving an inverse problem using Zeeman frequencies against various launching heights. Relative uncertainty due to the spatial inhomogeneity was estimated to be less than 10^(-18) from the field map.

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**Optical Phase Locking of DBR Laser for Atomic Gravimeter #1211#**

Sangmin Lee{2}, Sang Eon Park{2}, Sang-Bum Lee{1}, Hyun-Gue Hong{1}, Myoung-Sun Heo{1}, Taeg Yong Kwon{1}
{1}KRISS, Korea, South; {2}KRISS,UST, Korea, South

We present OPL of two DBR lasers to be used for an Rb atomic gravimeter developing at KRISS. Frequency difference of two lasers is 6.9 GHz which is the frequency near 87Rb ground hyperfine splitting. The OPL loop bandwidth is approximately 10 MHz, and the integrated phase variance is 0.29 rad^2.

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**On Efficiency of Laser Pumping for Selective Hyperfine-Level Population in Cesium and Rubidium Atoms #1232#**

Vitaly Palchikov, Aleksander Magunov
FGUP VNIIFTRI, Russia

The optical pumping of the ground state hyperfine magnetic sublevels of 87Rb and 133Cs atoms is studied theoretically. Explicit expressions for the stationary populations of the “clock” sublevels during Fg ↔ Fe=Fg and Ff ↔ Fe=Ff transitions of corresponding D2 lines in linearly polarized laser fields are obtained versus the initial values

| B3P-H | Timekeeping, Time & Freq Transfer, GNSS Apps II | Poster Area |
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| Chair | Peter Whibberley | |

**The Method of Establishing and Maintaining the Interstellar Time Reference During Autonomous Operation of Satellites #1002#**

Xiang-Lei Wang, Wen-Jun Zhao
Beijing satellite navigation center, China

In order to improve the viability of satellite navigation system, we need to establish autonomous operation of interstellar satellite time reference; Because of the complex environmental conditions of space, the interstellar time system that needing to build itself has the capacity of discovering, rejecting outliers and repairing, in order to provide a continuous clock bias sequence for the establishment of satellite time reference. For establishing and maintaining the interstellar time reference based on autonomous operation of satellites, this paper propose that first detecting, rejecting and repairing outliers with the

Kaman algorithm in real time, then using the repaired GPS satellite clock bias to establish the time scale with the KPW algorithm. It is found that the interstellar time reference has a good long-term stability and short-term stability, which established with the above method by experiments.

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### The Method on Determining Invisible Satellite-Ground Clock Difference with Inter-Satellite-Link #1007#

Wei-Jin Qin, Pei Wei, Xu-Hai Yang
National Time Service Center, China

When the satellite elevation is 10°,visible arcs last about 7 hours, invisible arcs last about 17 hours. However, satellite-ground clock difference of invisible arc is obtained by predicting. Satellite-ground clock difference is limited to the prediction precision. Inter-satellite link is a new op-eration mode, operating on a few stations or no station. Due to the limitation of station layout, this paper proposes determining satellite-ground clock difference of invisible arc by way of inter-satellite link, using target satellite connecting station with relay satellite. Satellite-ground linkare composed oftarget satellite and station.Inter-satellite linkare composed oftarget satellite and relay satellite.It analyzes range of relay-satellite angle.In fact, there existmore relay-satellites.In order to use all therelay-satellites,clock difference of invisible arc is determined with weight. The weight criterion: the inverse square of STD of relative clock difference. The result shows: time-synchronization precision of satellite-ground is less than 0.3ns, std is less than 0.3ns.

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### Research on the Zoom Technique of GNSS Timing Signal Granularity #1011#

Jianfeng Wu, Yong-hui Hu, Fei Chen, Jian Xu, Zai-min He
National Time Service Center, CAS, China

The 1PPS signal is the standard output of GNSS timing receiver. 1PPS means one pulse per second. The pulse is used to synchronize the device to Universal Time Coordinated(UTC) or the GNSS system time, and it is the recovery of GNSS system time or UTC in the local tim-ing receiver. In a typical design, 1PPS signal is locked with the signal recovery of GNSS 1PPS. In order to correct the sawtooth error of 1PPS signal, we study the zoom technique of GNSS timing signal granularity, and propose an improved scheme. The programmable delay line technology is introduced in the improved scheme. The granularity of the programmable delay line device can reach 0.25ns. We propose a control algorithm which can realize the zoom of GNSS 1PPS's granularity by the combined with the programmable delay line device. This scheme allows for real-time correction of the quantization error and reduces the residual noise to about 1~2 nanoseconds peak to peak (pk-pk), and improves the instantaneous and short-term timing accuracy of GNSS 1PPS.References.

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### A Paper Clock Prediction Model for UTC(TL) #1037#

Shinn Yan Lin
TL, Taiwan

A modified paper clock timescale weighted after removing the linearized frequency drift of each cesium clock in a 12-cesium-clock ensemble was used to be the mid-term prediction

reference before the announcement of the BIPM Circular T. To get a stable paper clock time scale, we investigated the noise patterns of each cesium clock in ensemble and found their noise were dominated by white noise when the average time was less than 30~40 days. A steering strategy using both proportional and derivative control algorithm would let UTC(TL) toward the paper clock time scale.

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**Design of a New Calibration Device for Two-Way Satellite Time and Frequency Transfer Station #1054#**

Xueyun Wang, Hang Yu, Shengkang Zhang, Liang Wang, Chao Wang, Haifeng Wang, Peng Wang

Beijing Institute of Metrology and Measurement, China

A new calibration device for TWSTFT has been developed recently at Beijing Institute of Radio Metrology and Measurement (BIRMM) .The signal paths inside calibration device is bidirectional which allow both the transmission and receiving signal passed, so the delay difference of the transmission and receiving inside calibration device almost be zero. The calibration device works on Ku-band. To evaluate the performance of the BIRMM calibration device, a local TWSTFT experiments was done with SATRE modem. The measurement results show that the time delay difference was quite small instability with standard deviation (1 σ) equal to 0.17ns.

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**Application of New Time Receivers in GLONASS #1066#**

Alexandr Bandura, Peter Bogdanov, Maksim German

Russian Institute of Radionavigation and Time, Russia

Till recently, time scale comparisons between GLONASS Central Synchronizers (CS) and State Time and Frequency Reference (STFR) have been performed with using Reference Equipment at CS and TTS-3 receiver at STFR. At the end of 2014 new equipment for time scale comparisons was additionally installed at CS and STFR: Time Transfer Unit TTU-1 developed at RIRT on the basis of 36-channel GLONASS/GPS receiver for SP signals in L1/L2 frequency bands " at the Main CS and a new GTR-51 time receiver for SP and P signals in L1/L2 frequency bands " at STFR. In 2015 the new equipment at CS and STFR was tested and the new accuracy results were obtained.

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**A Method to Verify the P1-P2 Hardware Calibration in GNSS Receiving Systems Dedicated to Time Transfer #1091#**

Wei Huang, Pascale Defraigne

Royal Observatory of Belgium, Belgium

The measurements from Global Navigation Satellite Systems (GNSS) are widely used for accurate time transfer and time dissemination, but first the hardware delays of the signals across the GNSS receiving system (antenna, cables and receiver) have to be determined by calibration. In this study we propose a strategy to verify the consistence between the hardware calibrations for the different frequencies (GPS P1 and P2 in this case) and to monitor the stability of these inter-frequency hardware delays.

**Carrier-Phase Two-Way Satellite Frequency Transfer Between OP and PTB** **#1104#**

Miho Fujieda{2}, Joseph Achkar{1}, Franziska Riedel{3}, Hiroshi Takiguchi{2}, Erik Benkler{3}, Michel Abgrall{1}, Jocelyne Guéna{1}, Stefan Weyers{3}, Dirk Piester{3}
{1}LNE-SYRTE, France; {2}NICT, Japan; {3}PTB, Germany

We demonstrate advanced two-way satellite frequency transfer using the carrier-phase information (TWCP) between OP and PTB.In this report, the evaluation of TWCP system configuration and comparison results of atomic fountain frequency standards are presented.

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**The Development of GPS/BDS Time Transfer System** **#1105#**

Hongbo Wang, Hang Yi, Shengkang Zhang, Haifeng Wang, Fan Shi, Xueyun Wang
Beijing Institute of Radio Metrology and Measurement, China

BIRM has developed a GNSS time transfer system which supports both GPS and Beidou system. This paper describes the development of the hardware system and the data processing software of the system. CGTTS V3 file and Rinex 3.02 file including Beidou and GPS could be generated, and all the GPS/BDS satellite observations could be updated in real-time. The time transfer results from GPS and Beidou system are compared.

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**Determination of Differential Delays of Earth Stations in Paris and Torino from the Calibrated OP-IT TWSTFT Link** **#1106#**

Joseph Achkar{2}, Ilaria Sesia{1}, Daniele Rovera{2}
{1}INRIM, Italy; {2}LNE-SYRTE, France

Two-Way Satellite Time and Frequency Transfer (TWSTFT) technique is used in most of the metrology institutes as the primary link method for time-scales comparisons. A major advantage of this technique is direct comparisons of time-scales in almost real time using remote earth stations in microwave links through a geostationary satellite. Four earth stations implemented in LNE-SYRTE and INRIM are used. The differential delays of each pair of stations are thus determined from measurements of the various two-way links, relying the measurements taken by the calibrated OP01-IT02 TWSTFT link.

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**Remote Time and Frequency Transfer Experiment Based on BeiDou Common View** **#1108#**

Hang Yi, Hongbo Wang, Shengkang Zhang, Haifeng Wang, Fan Shi
Beijing Institute of Radio Metrology and Measurement, China

BeiDou navigation satellite system (BDS) is now offering an independent regional service for the Asia-Pacific region and it is going to offer global positioning service by 2020. And BDS will be another choice for remote precise time and frequency transfer. In this paper,we made some remote time and frequency transfer experiment based BD common view and checked the results by the TWSTFT experiment. Also the common view precision results using GPS and BD are compared in this paper.

**Relativistic Effect Correction for Clock Transport** **#1116#**

Hiroshi Takiguchi, Tadahiro Gotoh, Miho Fujieda, Fumimaru Nakagawa, Hideki Narita, Kensuke Matsubara, Kuniyasu Imamura, Hiroyuki Ito, Jun Amagai, Yuko Hanado

National Institute of Information and Communications Technology, Japan

NICT carried out the first calibration of the GPS link between Koganei and Kobe by using GPS, TWSTFT and Clock Transport (CT). We presented the result of the calibration in last EFTF. The obtained differential correction of GPS link by GPS, TWSTFT and CT were 102.5, 102.1 and 104.9 ns respectively. The CT result showed a discrepancy of 2 ns, and we concluded that the reason of this discrepancy is the uncertainty of the CT technique. This time, we applied the relativistic effect correction for CT and we confirmed a good agreement of the results obtained by their three techniques.

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**Generation of a Time Scale at ESOC** **#1135#**

Steffen Braun{1}, Simon de Fine Licht{2}, Maria Ramos{3}, Erik Schönemann{1}

{1}ESOC, Germany; {2}None, Sweden; {3}SERCO / ESOC, Germany

In April 2013, an activity for generating a time scale at ESOC using the three available AHM was started. The scale is compared to existing UTC time scales using the IGS Rapid orbit and clock products, the PPP-based time transfer results are obtained with ESA's GNSS data processing software package NAPEOS. Proprietary software has been developed for the steering, monitoring, post-processing and generation of the BIPM files. The time scale will be used by the ESOC Navigation Office for the enhancement of their clock products, and by the ESOC Ground Systems Division for time transfer to the ESTRACK Deep Space Stations.

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**First Steps Towards a Time Integrity Service for EGNSS Systems, in the DEMETRA Project** **#1150#**

Ilaria Sesia{2}, Patrizia Tavella{2}, Giovanna Signorile{2}, Alice Cernigliaro{1}, Franco Fiasca{1}, Pascale Defraigne{3}, Lorenzo Galleani{4}

{1}AIZOON, Italy; {2}Istituto Nazionale di Ricerca Metrologica, Italy; {3}Observatoire Royal de Belgique, Belgium; {4}Politecnico di Torino, Italy

DEMETRA (DEMonstrator of EGNSS services based on Time Reference Architecture) is a research project co-funded by the European Union through the Horizon 2020 program, aiming to develop and experiment time dissemination services based on the European GNSS. An important aspect that will be analysed in the frame of this project is the capability to deliver a time integrity service to the GNSS users, providing integrity information to improve user timing accuracy as well as positioning. The DEMETRA Time Integrity Service is intended as a first step to test the concepts and performance of a Galileo time integrity system.

**Interference Detection and Countermeasures in a GPS- Disciplined Chip-Scale Atomic Clock** **#1199#**

Aril Schultzen{1}, Harald Hauglin{1}, Tim Dunker{1}, Sverre Holm{2}
{1}Justervesenet, Norway; {2}University of Oslo, Norway

We describe a smart clock controller (SMACC) intended to complement a commercial disciplined clock so that it becomes ‘spoof proof’, i.e. hardened against several classes of GPS jamming and spoofing attacks. The controller uses a multi receiver, multifactorial approach to evaluate the validity/integrity of received GPS signals based on a number of observables as well as clock correction modelling.

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**GNSS Disciplined Oscillators: an Approach Based on Real-Time Steering Over the Internet with Certification** **#1205#**

Nilufer Ozdemir{2}, Pascale Defraigne{2}, Giancarlo Cerretto{1}, Elena Cantoni{1}, Patrizia Tavella{1}
{1}Istituto Nazionale di Ricerca Metrologica, Italy; {2}Royal Observatory of Belgium, Belgium

GPS disciplined oscillators based on the Common-View approach have already been proposed and implemented. In this work, we propose another system architecture: the local oscillator will be slaved to a remote reference time scale by means of time and frequency corrections streamed over the Internet in real time. Moreover, a certificate will be issued to the user, giving the time and frequency offset of the local oscillator with respect to the remote reference time scale. If such a reference time scale is a local realization of UTC, the certification allows the user to trace its clock to UTC.

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**A Rotating Fan-Beam Radiation Model for the Pulse Duration and Frequency Spectrum of Pulsar Radiation** **#1214#**

Michael Underhill
Underhill Research Limited, United Kingdom

The assumption of a rotating fan beam of broadband RF radiation would appear to give a good fit to the observed pulse length to period ratio and pulse amplitude statistics of pulsars. The radiation pattern is assumed to arise from standing waves in multiple radiating layers of (ionospheric) plasma above and around the equator of the pulsar. The frequencies of the multiple layers form a comb spectrum with components spaced at the pulsar rotation frequency. The pulse length to period ratio is found to be inversely proportional to the number layers, typically being about 40 in number.

| B3P-J | Optical Frequency Standards & Applications II | Poster Area |
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| Chair | Helen Margolis | |

**Narrow-Linewidth, Micro-Integrated UV Laser System for Precision Spectroscopy Applications** **#1033#**

Ahmad Bawamia{1}, Mandy Krüger{1}, Christian Kürbis{1}, Andreas Wicht{1}, Günther Erbert{1}, Guenther Tränkle{1}, Stephan Hannig{3}, Piet Schmidt{3}, Sana Amairi Pyka{2}, Achim Peters{2}
{1}Ferdinand-Braun-Institut, Leibniz-Institut fuer Hoechstfrequenztechnik, Germany; {2}Humboldt Universitaet zu Berlin, Germany; {3}Physikalisch-Technische Bundestanstalt, Germany

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

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**A Preliminary Prototype of Laser Frequency Stabilization for Space-Borne Interferometry Missions** **#1052#**

Yingxin Luo, Hsien-Chi Yeh
Huazhong University of Science and Technology, China

A prototype of laser frequency stabilization system for inter-satellite laser ranging is presented. This system used Pound-Drever-Hall (PDH) method to stabilize the laser frequency and hydroxide-catalysis bonding to manufacture the Fabry-Pérot (FP) cavity and its mode-matching optical layout on a quasi-monolithic ULE optical bench. All-fiber devices were applied for the PDH optical link, and an in-house-designed digital controller was developed for automatic laser frequency locking and re-locking, which can benefit autonomous operations on board. Preliminary result shows the frequency noise of this prototype less than 30 Hz/Hz^1/2 from 0.7 Hz to 10 Hz.

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**Interrogating Optical Clocks Beyond the Coherence Limit of the Clock Laser** **#1065#**

Marcin Bober{1}, Ali Al-Masoudi{2}, Sören Dörscher{2}, Sebastian Häfner{2}, Christian Lisdat{2}, Uwe Sterr{2}
{1}Nicolaus Copernicus University, Poland; {2}Physikalisch-Technische Bundesanstalt, Germany

We will present a novel interrogation scheme that will allow building a compound clock using different species with probe times longer than the coherence time of the clock laser. The proposed technique utilizes a correlated interrogation sequence of two atomic clocks with one clock laser to resolve the phase ambiguity apparent in Ramsey interrogation beyond the coherence limit of the interrogation laser.

**Rb-Stabilized Optical Frequency Reference at 1572 nm #1073#**

William Moreno, Renaud Matthey, Florian Gruet, Pierre Brochard, Stephane Schilt, Gaetano Mileti

Université de Neuchâtel, Laboratoire Temps-fréquence, Switzerland

In the framework of an onboard optical reference laser system, a DFB laser emitting at 1572 nm is offset-locked to a frequency stabilized optical frequency comb. The comb is generated from the radiation of a DFB laser emitting at 1560 nm that frequency-doubled and stabilized to a sub-Doppler Rb absorption using a 2-cm long vapor glass cell. At 1572 nm, a relative frequency stability of 1·10-11 at 1 s has been obtained, reaching < 4·10-12 from 3,000 s up to 3 days. The accuracy and reproducibility of the locking point to the 87Rb D2 line is also presented.

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**A Highly Tunable Low-Drift Laser Referenced to an Atomic Transition# 1075#**

Tobias Leopold{2}, Lisa Schmöger{1}, Stefanie Feuchtenbeiner{1}, Christian Grebing{2}, Peter Micke{2}, Nils Scharnhorst{2}, Ian Leroux{2}, Steven Anthony King{2}, José Ramon Crespo López-Urrutia{1}, Piet Oliver Schmidt{2}

{1}Max-Planck-Institut für Kernphysik, Germany; {2}Physikalisch-Technische Bundesanstalt, Germany

We present a laser system for the resolution of an atomic transition line broadened to ~100 kHz in Ar^(13+) with a lifetime of 10 ms. A frequency reference with fractional instability below 10^(-10) is achieved by modulation transfer spectroscopy in a rubidium vapour cell. We transfer the absolute frequency stability of a reference laser to the spectroscopy laser via an evacuated transfer cavity. Resulting linewidth and frequency fluctuations are kept below 50 kHz over time scales up to 10^5 seconds. We observe no linear drift on the kHz level over 90 h of continuous operation.

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**New Approaches in Deep Laser Cooling of Magnesium Atoms for Quantum Metrology #1076#**

Oleg Prudnikov{2}, Denis Brazhnikov{1}, Anatoly Bonert{1}, Andrey Goncharov{1}, Alexey Taichenachev{1}, Valeriy Yudin{2}

{1}Institute of Laser Physics SB RAS, Russia; {2}Novosibirsk State University, Russia

Laser cooling and trapping of neutral magnesium atoms have been theoretically analyzed in details. We have proposed two ways for overcoming long-standing problem on getting large number of ultracold magnesium atoms for metrological purposes. Our theory is based on widely used semiclassical approximation as well as on quantum treatment with full account for the atomic recoil effect. Significant differences between the results of two approaches explain many existing problems with deep cooling of magnesium atoms by means of laser radiation. Both of the proposed solutions can allow getting ~10^6 of Mg atoms owning temperature at the level of 10 microK.

**An Yb Optical Lattice Clock at KRISS: Current Status** **#1078#**

Huidong Kim, Dai-Hyuk Yu, Chang Yong Park, Won-Kyu Lee, Myoung-Sun Heo, Sang Eon Park, Sang-Bum Lee, Hyun-Gue Hong, Taeg Yong Kwon
Korea Research Institute of Standards and Science, Korea, South

We report the current status of an Yb optical lattice clock at Korea Research Institute of Standards and Science (KRISS), Korea. We are making efforts to evaluate the lattice laser induced shifts with uncertainty at or below 10-18 level by developing a build-up cavity to enhance the optical lattice depth. The finesse of the cavity is about 155 and trap depth of up to 2000 recoil energy is expected to be reached. To reduce blackbody radiation (BBR) shift, we are developing a thermal shield with minimized temperature distribution.

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**Transferring Frequency Stability Simultaneously to Multiple Wavelengths with an Optical Frequency Comb** **#1085#**

Fred Baynes, Antoine Rolland, Steven King, Ross Williams, Stephen Kyriacou, Patrick Gill, Helen Margolis
National Physical Laboratory, United Kingdom

Many applications, such as atomic clocks and long distance optical fibre links will benefit from a local oscillator with improved frequency stability. Here we report using an optical frequency comb to simultaneously transfer the stability of a 1064 nm ultra-stable optical cavity to 4 independent optical atomic clock-relevant wavelengths ranging from 674 nm to 934 nm, a telecom laser at 1542 nm and a microwave signal at 9.2 GHz.

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**Development of Optical Clocks Based on Strontium Atoms: First Observed Clock-Transition Spectrum** **#1088#**

Sergey Strelkin, Oleg Berdasov, A. Galyshev, A. Gribov, K. Khabarova, N. Kolachevsky, S. Slyusarev
FSUE VNIIFTRI, Russia

We report about first results in clock transition spectroscopy of SR88 in FSUE VNIIFTRI lab. We have about 10^4 atoms in optical lattice and we have reached linewidth of clock transition about 100Hz.

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**All Fiber Coupled Ion Trap for Metrology** **#1120#**

Callan Jobson, Willian Groom, Matthias Keller
University of Sussex, United Kingdom

We present an ion trap system with integrated optics for delivering laser radiation to single trapped ions and to collect their fluorescence. Utilizing this compact system we develop a low volume (< few liters), low power (<100W), portable atomic clock based on trapped calcium ions.

**PTB's Transportable Strontium Lattice Clock #1124#**

Jacopo Grotti, Silvio Koller, Stefan Vogt, Sebastian Häfner, Sofia Herbers, Uwe Sterr, Christian Lisdat
Physikalisch-Technische Bundesanstalt, Germany

We want to present the progress on our transportable lattice clock, which has been evaluated at the low 10^{-16} level. A comparison measurement to a stationary strontium clock has been performed. We also report the results of the first transportation of the lattice clock.

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**Phase Lock and Laser Characterization for the Probing of Trapped Ca+ Ions #1131#**

M. Collombon, R. Khayatzadeh, Gaetan Hagel, M. Houssin, C. Champenois, M. Knoop
Université d'Aix-Marseille, France

Phase locking of three different laser involved in the Ca+ ion spectroscopy by using a frequency comb.

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**Cavity-Assisted Non Destructive Detection in a Strontium Optical Lattice Clock #1142#**

Grégoire Vallet, Eva Bookjans, Slawomir Bilicki, Rodolphe Letargat, Jérôme Lodewyck
LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Pa, France

Here we report progress on the experimental implementation and theoretical evaluation of a cavity-assisted non destructive detection on one of our strontium clock. This detection will help taking the clock towards, and eventually beyond, the QPN limit. Such a scheme permits to recycle the atoms from an interrogation to another, reducing the duty cycle of the clock. Moreover beating the QPN means entering the quantum realm, enabling quantum weak measurement and cavity spin squeezing via Quantum Non Demolition measurements (QND).

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**First Results for the Offset Frequency Stabilization via Opto-Optical Modulation of an All-in Fiber Single Walled Carbon Nanotube Erbium Femtosecond Laser #1169#**

Sebastian Schweyer{2}, Khanh Kieu{5}, Philipp Putzer{1}, Eder Bastian{1}, Andreas Kölnberger{1}, Norbert Lemke{1}, Reinhard Kienberger{3}, Ulrich Schreiber{4}
{1}OHB System AG, Germany; {2}Technische Universität München, FESG, Physik Department E11, Germany; {3}Technische Universität München, Physik Department E11, Germany; {4}Technische University München, FESG, Germany; {5}University of Arizona, College of Optical Sciences, United States

The opto-optical modulation (OOM) technique was recently demonstrated for the stabilization of a solid state SESAM modelocked femtosecond frequency comb. In the here presented work the OOM technique for an all in fiber tapered carbon nanotube

femtosecond laser is investigated, which can be used whether to stabilize the laser's repetition rate or carrier envelope offset frequency.

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**Compact Self-Referenced Femtosecond Er-Doped Fiber Laser Oscillator Without External Power Amplification** **#1176#**

Jin-Long Peng, Tze-An Liu, Yuh-Chuan Cheng
Center for Measurement Standards, Taiwan

A femtosecond Er-doped fiber laser oscillator with repetition rate of 100 MHz is employed to directly drive a highly nonlinear optical fiber, which generates an octave-spanning supercontinuum spectrum without using external power amplification. Compact self-referenced fiber laser comb is realized with the f-to-2f interferometer to detect the carrier-envelope-offset frequency.

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**Metrological Characterization of the INRIM Yb Lattice Clock** **#1180#**

Benjamin Rauf, Marco Pizzocaro, Pierre Thoumany, Gianmaria Milani, Giacomo Bolognesi, Filippo Bregolin, Michele Gozzelino, Filippo Levi, Davide Calonico
INRIM, Italy

We present INRIM's optical lattice clock based on neutral 171Yb atoms. The clock is currently under operation and we evaluated the first metrological characterization. We completed the set-up adding an efficient spin-polarization. The results for the uncertainty budget and the clock's stability will be described and the perspectives of the full metrological characterization together with future experiments.

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**Sympathetic Cooling Al+ Ion with Ca+ Ion for Optical Clock** **#1184#**

Junjuan Shang, Kaifeng Cui, Shaomao Wang, Sijia Chao, Jian Cao, Hualin Shu, Xueren Huang
Wuhan Institue of Physics & Mathematics of Chinese Academy of Sciences, China

In this work, We use one laser cooled Ca+ to sympathetic cool a Al+ in linear Paul trap. In order to increase loading aluminum ion efficiency , Compare to using laser ablation atom producing ion ,we got a much lower velocity atoms sprayed from a home-made atom oven, which will make the sympathetic cooling much easier. By the method of precisely measuring the RF resonance frequency of the ion pair ,finally We proved we obtained the Al+-Ca+ ion pair witch will be used to QLS optical frequency standard. by sideband cooling method we succeed in cooling the Ca+ to the ground state with more than possibility 95% .The Quantum-logic-Spectroscopy experiment is in progress.

**Very High Sensitivity Laser Gyroscope for General Relativity Tests in a Ground Laboratory #1210#**

Jacopo Belfi{2}, Nicolò Beverini{7}, Giorgio Carelli{7}, Angela Di Virgilio{2}, Enrico Maccioni{7}, Alessandro Beghi{6}, Davide Cuccato{6}, Alberto Donazzan{6}, Giampiero Naletto{6}, Antonello Ortolan{3}, Alberto Porzio{1}, Carlo Altucci{5}, Raffaele Velotta{5}, Angelo Tartaglia{4}
{1}CNR-SPIN Napoli, Italy; {2}INFN- Sezione di Pisa, Italy; {3}INFN-Lab. Naz. Legnaro, Italy; {4}Politecnico di Torino, Italy; {5}Universita' di Napoli, Italy; {6}Universita' di Padova, Italy; {7}Universita' di Pisa, Italy

Observation of the metric frame dragging predicted by General Relativity, produced by the Earth rotating mass (Lense-Thirring effect) in a ground laboratory is the final goal of INFN GINGER project. Two laser gyroscopes have been developed. The first is a square gyroscope of 1.60 m of side devoted to test the procedure to optimize the control of the ring geometry in order to achieve the required sensitivity. The second, 3.60 m of side, is located in INFN Gran Sasso underground laboratory, beneath 1000 meters of rock in the Apennine mountains. The aim is to verify the noise quality of the site, in view of an installation of a future large GINGER apparatus.

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**Iodine Absorption Cells Quality Measurements #1221#**

Jacopo Belfi{2}, Nicolò Beverini{7}, Giorgio Carelli{7}, Angela Di Virgilio{2}, Enrico Maccioni{7}, Alessandro Beghi{6}, Davide Cuccato{6}, Alberto Donazzan{6}, Giampiero Naletto{6}, Antonello Ortolan{3}, Alberto Porzio{1}, Carlo Altucci{5}, Raffaele Velotta{5}, Angelo Tartaglia{4}
{1}CNR-SPIN Napoli, Italy; {2}INFN- Sezione di Pisa, Italy; {3}INFN-Lab. Naz. Legnaro, Italy; {4}Politecnico di Torino, Italy; {5}Universita' di Napoli, Italy; {6}Universita' di Padova, Italy; {7}Universita' di Pisa, Italy

This work is oriented to comparison of methods for iodine absorption cells quality evaluation. Optical frequency references based on molecular iodine represent one of the most used references for stabilizion of laser standards working at visible spectral range. Molecular iodine offers rich spectra of strong and narrow absortion lines, but it is a media with high sensitivity for contamination the purity of iodine cells must be precisely controlled. This contribution compares traditional methods for iodine cells quality evaluation (laser induced fluorescence, frequency shifts) with proposed alternative method of linewidth measurement and summarizes the suitability of these methods for practical using.

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**Turn-Key 1 GHz Ti:Sapphire Frequency Comb with Enhanced Off-Set Locking Bandwidth #1236#**

Matthias Beck, Alan Cox, Tobias Plötzing, Marcel Indlekofer, Tushar Mandhyani, Philipp Leiprecht, Albrecht Bartels
Laser Quantum GmbH, Germany

In the early days of the frequency comb mode-locked Ti:Sapphire lasers were the domi-nant light sources serving this ground-breaking technology. Amongst them, those with a

repetition rate (fR) around 1GHz were often favored over systems nearer 100MHz due to their larger mode spacing, higher average power coherent super-continuum output and consequently higher power per mode.

**B4L-A Ion Clocks P/X001**

**Chair Tai Hyun Yoon**

### 16:00 Progress Towards a 88Sr+ Single-Ion Clock with a Fractional Uncertainty at the 3 x 10^-18 Level #1100#

Pierre Dubé{1}, Bin Jian{1}, Alan Madej{2}
{1}National Research Council Camada, Canada; {2}York University, Canada

The Sr+ ion optical clock at NRC has an evaluated fractional uncertainty of 1.2 x 10-17. The dominant source of uncertainty is currently the part of the blackbody radiation (BBR) shift that depends on the thermal field evaluation. The BBR shift uncertainty caused by the polarizability parameter has been reduced to below 1 x 10-18 recently. We will present advances made in controlling the systematic shifts of the Sr+ clock transition, including progress towards a new determination of the BBR field. An improved BBR field evaluation is expected to reduce the Sr+ uncertainty to the low 10-18 level.

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### 16:20 Optical Atomic Clock Measurements in 171Yb+ #1097#

Peter Nisbet-Jones{1}, Rachel Godun{1}, Steven King{1}, Jonathan Jones{1}, Charles Baynham{1}, Kai Bongs{2}, Patrick Baird{3}, Patrick Gill{1}
{1}NPL, United Kingdom; {2}University of Birmingham, United Kingdom; {3}University of Oxford, United Kingdom

Clocks based on singly-ionised ytterbium are strong candidates for an optical redefinition of the SI second. We report on advances in the understanding and control of all systematic perturbations, along with advances in the stability, robustness, and reliability of the clock.

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### 16:40 Improved Uncertainty Evaluations of the 171Yb+ Single-Ion Optical Clocks of PTB #1122#

Nils Huntemann, Christian Sanner, Sergey Kuznetsov, Burghard Lipphardt, Christian Tamm, Ekkehard Peik
Physikalisch-Technische Bundesanstalt, Germany

171Yb+ provides two reference transitions that are adequate for the realization of an optical frequency standard: an electric quadrupole (E2) transition at 436 nm and an electric octupole (E3) transition at 467 nm. We report on a comparison of two independently operating single-ion clocks that use the E2 transition as the reference and a measurement of the ratio of the E3 and the E2 transition frequency. To avoid the light shift of the E3 transition frequency, coherent composite pulse sequences were proposed over the last years. We present a conceptually different approach leading to a universal pulse-defect immunity.

**17:00 Frequency Comparison of Two 40Ca+ Optical Clocks with an Uncertainty at the 10^-17 Level** **#1174#**

Yao Huang, Hua Guan, Wu Bian, Kelin Gao
Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, China

Based upon an over-one-month frequency comparison of two 40Ca+ optical clocks, the frequency difference between the two clocks is measured to be 3.2 × 10^−17 with a measurement uncertainty of 5.5 × 10^−17, considering both the statistic (1.9 × 10^−17) and the systematic (5.1 × 10^−17) uncertainties. This is the first performance of a 40Ca+ clock better than that of Cs fountains. A fractional stability of 7 × 10^−17 in 20 000 s of averaging time is achieved. The evaluation of the two clocks shows that the shift caused by the micromotion in one of the two clocks limits the uncertainty of the comparison. By carefully compensating the micromotion, the absolute frequency of the clock transition is measured to be 411 042 19 129 776 401.7(1.1) Hz.

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**17:20 Frequency Ratio of a 171Yb+ Single Ion Clock and a 87Sr Lattice Clock with 2 x 10^-17 Uncertainty** **#1123#**

Nils Huntemann, Sören Dörscher, Ali Al-Masoudi, Stephan Falke, Nathan Lemke, Sebastian Häfner, Christian Grebing, Burghard Lipphardt, Christian Sanner, Christian Tamm, Uwe Sterr, Christian Lisdat, Ekkehard Peik
Physikalisch-Technische Bundesanstalt, Germany

We report on a direct comparison of two very different optical clocks. One is based on the 2S1/2-2F7/2 electric octupole transition of a single 171Yb+ ion stored in a radio-frequency Paul trap and the other clock realizes the 1S0-3P0 transition of many 87Sr atoms confined in an optical lattice near the magic wavelength. More than eighty hours of acquired data result in a statistical uncertainty of 1.3E-17, and yield the frequency ratio of the two clocks with a total fractional uncertainty of 2.4E-17, which is the smallest uncertainty achieved for clocks of different type to date.

| B4L-B | Timing Networks and Applications | P/L001 |
|---|---|---|
| Chair | Patrizia Tavella | |

**16:00 Network Time Security Specification: Protecting Network-Based Time Synchronization (Invited)** **#1074#**

Dieter Sibold, Kristof Teichel
Physikalisch-Technische Bundesanstalt (PTB), Germany

We present the Network Time Security specification (NTS), which is designed to protect time synchronization protocols, especially the Network Time Protocol (NTP) but also the Precision Time Protocol (PTP). Apart from common security requirements, such as protection of integrity and authenticity, NTS also meets specific security requirements formulated for time synchronization protocols by the IETF in RFC 7384. The specification work to apply NTS to NTP is done within the IETF, whereas the aspects of NTS in the context of PTP are considered by IEEE’s P1588 working group.

### 16:40 Sub-Nanosecond Synchronization Accuracy for Time-Sensitive Applications on Industrial Networks #1094#

José Luis Gutiérrez{2}, César Prados{1}, Javier Díaz{2}
{1}GSI Helmholtz Centre for Heavy Ion Research, Germany; {2}University of Granada, Spain

This contribution proposes a change of approach for the White Rabbit technology to become a timing solution with strong focus on Smart Grid. It includes a new design following IEC 61850, where new developments make possible for WR devices to work as Transparent Clocks (TCs) and hence, maximizing the interoperability with other industrial devices. Moreover, the utilization of TCs offers better synchronization results since PTP messages include the entire network delay considering all TCs as a unique fiber. In addition, it eases the development of redundancy protocols like HSR or PRP to guarantee the delivery and reception of critical services such as timing and substation events.

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### 17:00 Towards Sub-Nanosecond Synchronization of a Telecom Network by Fiber Optic Distribution of UTC(K) #1041#

Lukasz Sliwczynski{1}, Przemyslaw Krehlik{1}, Helmut Imlau{2}, Horst Ender{2}, Harald Schnatz{3}, Dirk Piester{3}, Andreas Bauch{3}
{1}AGH University of Science and Technology, Poland; {2}Deutsche Telekom Technik GmbH, Germany; {3}Physikalisch-Technische Bundesanstalt, Germany

We present the results of our four-months long experiments performed between PTB in Braunschweig and Deutsche Telekom center in Bremen with sending time and frequency signals via fiber. The purpose is synchronization and monitoring of enhanced Primary Reference Time Clocks (ePRTC) that are required to assure continous and robust operation of telekom network. The measurements were performed in parallel using the methods and means typical for telecom operators, and common in the T&F metrology domain. The results show that the synchronization significantly below 1 nanosecond between a UTC laboratory and a telecom center may be obtained.

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### 17:20 Development of an Ultra-Stable Frequency Transfer in a Commercial Fiber-Optic WDM-Network #1119#

Per Olof Hedekvist{2}, Sven-Christian Ebenhag{2}, Martin Zelan{2}, Magnus Karlsson{1}, Börje Josefsson{3}
{1}Chalmers, Sweden; {2}SP, Sweden; {3}SUNET, Sweden

A technique to enable actively stabilized optical frequency transfer and dissemination over deployed communication fiber networks is developed and implemented between SP and Chalmers, a 60 km distance in the Swedish University Computer Network. The stability and achievable performance of the transfer when utilizing two-way transfer in duplex fibers is characterized and evaluated with respect to requirements.

**B4L-C Atom Interferometers P/L002**

**Chair Arnaud Landragin**

**16:00 The LNE-SYRTE Cold Atom Gravimeter (Invited) #1195#**

Franck Pereira Dos Santos, Pierre Gillot, Bing Cheng, Sébastien Merlet
LNE-SYRTE, France

I will present the absolute Cold Atom Gravimeter (CAG) which has been developed in the frame of the LNE watt balance project. This instrument has been operational since 2009, and participated successfully since then to three international comparison campaigns. It uses atom interferometry to perform an absolute measurement of the gravitational acceleration g, with a best sensitivity as low as 5.7 10^-9g/Hz, a high cycling rate of about 3 Hz and a relative accuracy of 4 parts in 10^9.

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**16:40 Continuous Cold-Atom Inertial Sensor with 0.9 nrad.s^-1 Rotation Stability #1036#**

Bess Fang, Indranil Dutta, Denis Savoie, Bertrand Venon, Carlos Leonardo Garrido Alzar, Remi Geiger, Arnaud Landragin
LNE-SYRTE, France

We report the operation of a cold atom inertial sensor in a joint interrogation scheme, where we simultaneously prepare a cold atom source and operate an atom interferometer (AI) to eliminate the dead times. We show that such continuous operation improves the short term sensitivity of AIs, by demonstrating a record rotation sensitivity of 90 nrad/s/\sqrt{Hz} in a cold atom gyroscope of 11 cm^2 Sagnac area. We also demonstrate a rotation stability below 1 nrad/s after 10^4 s of integration time, which improves previous results by more than an order of magnitude. We expect that the continuous operation of cold atom inertial sensors will allow to bene fit from the full sensitivity potential of large area AIs, determined by the quantum noise limit.

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**17:00 Finite Size Effect on Scale Factor for an Atom Ball Gyroscope #1018#**

Bruno Pelle, Gregory Hoth, Stefan Riedl, John Kitching, Elizabeth Donley
National Institute of Standards and Technology, United States

An atom interferometer scheme that allows a simultaneous measurement of 2-axis rotations and 1-axis acceleration in a 1 cm3 volume will be presented. To decouple phase shifts induced by rotation and acceleration with a single atomic source, we extend the Point-Source-Interferometry technique to the compact regime. Then the atom cloud can no longer be treated as a point source, introducing a bias in the scale factor from the point-source limit. After obtaining spatial interference fringes for short free-fall durations, we explored the scale factor deviation with different initial cloud sizes and observed the transition from the point-source to finite-size situations.

# Thursday 7th April

| | P/X001 | P/L001 | P/L002 |
|---|---|---|---|
| 8.40-<br>10.20 | C1L-A<br>**Frequency Combs**<br>Chr: Harald Schnatz<br>Track: Optical Frequency Standards and Applications | C1L-B<br>**Caesium Frequency Standards**<br>Chr: Krzysztof Szymaniec<br>Track: Microwave Frequency Standards | C1L-C<br>**Low Noise Synthesis**<br>Chr: Mike Underhill<br>Track: Oscillators, Synthesizers, Noise, & Circuit Techniques |
| 10.20 | Coffee / tea break | | |
| 10:50-<br>12.30 | C2L-A<br>**Lattice Clocks II**<br>Chr: Jérome Lodewyck<br>Track: Optical Frequency Standards and Applications | C2L-B<br>**CPT Cell Standards**<br>Chr: Salvatore Micalizio<br>Track: Microwave Frequency Standards | C2L-C<br>**Opto-electronics and Microwave Oscillators**<br>Chr: Gilles Cibiel<br>Track: Oscillators, Synthesizers, Noise, & Circuit Techniques |
| 12.30 | Lunch | | |
| 14:00-<br>15.40 | C3L-A<br>**Optical Oscillators and Spectroscopy**<br>Chr: Thomas Südmeyer<br>Track: Optical Frequency Standards and Applications | C3L-B<br>**Optical Fibre Frequency Transfer**<br>Chr: Paul-Eric Pottie<br>Track: Timekeeping, Time and Frequency Transfer, GNSS Applications | C3L-C<br>**Microwave Frequency Standards**<br>Chr: Christoph Affolderbach<br>Track: Microwave Frequency Standards |
| 15.40 | Coffee / tea break | | |
| 16.00 | Laboratory Tours (see sign-up sheets at reception if interested) | | |

| C1L-A | Frequency Combs | P/X001 |
|---|---|---|
| Chair | Harald Schnatz | |

**08:40 Ultra Low Noise Er:fiber Frequency Comb Comparison #1224#**

Bruno Pelle, Gregory Hoth, Stefan Riedl, John Kitching, Elizabeth Donley
National Institute of Standards and Technology, United States

We have developed a new generation of fiber based frequency combs with ultra high stability based on all pm fibers and NOLM mode locking. An integrated phase noise below 60 mrad (100 Hz " 2 MHz) is reached for the full frequency comb. The locked beat signals exhibit an Allan deviation (ADEV) below 10^-16 at 1s. For a full evaluation of short and long term performance we have built and compared two such systems. Both systems are locked to the same 1542nm optical reference laser and the two combs are compared via a direct beat signal at 1µm. In the direct comparison we reach an ADEV of 1 x 10^-16 at 1 sec and the 10^-20 range after 20000 sec, by far surpasing current optical clocks.

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**09:00 State-of-the-Art Ultra-Low Phase Noise Photonic Microwave Generation and Characterization #1171#**

Romain Bouchand{3}, Xiaopeng Xie{3}, Daniele Nicolodi{3}, Pierre-Alain Tremblin{4}, Giorgio Santarelli{4}, Christophe Alexandre{2}, Michele Giunta{5}, Matthias Lezius{5}, Wolfgang Haensel{5}, Ronald Holzwarth{5}, Datta Shubhashish{1}, Joshi Abhay{1}, Yann Le Coq{3}
{1}Discovery Semiconductors, Inc., United States; {2}LNE-CNAM, France; {3}LNE-SYRTE, France; {4}LP2N, France; {5}Menlo Systems GmbH, Germany

Many applications such as telecommunication, radar, deep-space navigation systems and pre-cision microwave spectroscopy are calling for ultra-stable microwave signals. Photonic generation of such signals is of particular interest because it allows transferring the unsurpassed spectral purity of ultra-stable continuous wave lasers to the microwave domain. The conversion from optical to micro-wave is done by synchronization of the repetition rate of a femto-second laser with an ultra-stable op-tical frequency reference. The microwave signal is further extracted via fast photo-detection of the optical pulse train. However, the photo-detection process itself introduces excess phase noise hereby limiting the stability of the optically generated microwave signal. The main limits on the purity of the microwave signal generated are the amplitude-to-phase conversion (APC) combined with intensity noise of the femto-second laser and the shot and thermal noise from the photodetector.

**09:20 Carrier-Envelope Offset Characterization in a Semiconductor Modelocked Laser Without f-to-2f Interferometry #1070#**

Pierre Brochard{2}, Nayara Jornod{2}, Valentin Wittwer{2}, Stéphane Schilt{2}, Dominik Waldburger{1}, Sandro Link{1}, Cesare Alfieri{1}, Matthias Golling{1}, Laurent Devenoges{3}, Jacques Morel{3}, Ursula Keller{1}, Thomas Südmeyer{2}
{1}ETH Zurich, Switzerland; {2}Laboratoire Temps-Fréquence, Switzerland; {3}METAS, Switzerland

We measured for the first time the noise properties and the modulation response of the free-running carrier-envelop offset (CEO) frequency in a semiconductor modelocked laser. We used a novel characterization method that does not involve standard f-to-2f interferometry, but makes use of an appropriate combination of signals obtained from the comb and a reference continuous-wave laser. We first present a validation of the method in an Er:fiber comb, where the achieved results are in excellent agreement with reference data obtained by f-to-2f interferometry. Then we present an implementation of the method with a modelocked vertical external-cavity surface-emitting laser.

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**09:40 Efficient Carrier Envelope Offset Frequency Stabilization Through Gain Modulation via Stimulated Emission #1064#**

Lauriane Karlen, Gilles Buchs, Erwin Portuondo-Campa, Steve Lecomte
CSEM, Switzerland

A novel scheme for intra-cavity control of the carrier- envelope offset frequency (fCEO) of a modelocked Er:Yb:glass diode-pumped solid state laser based on the modulation of the laser gain via stimulated emission is demonstrated.

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**10:00 DFG Comb Showing Quadratic Scaling of the Phase Noise with Frequency #1128#**

Russell Kliese, Thomas Puppe, Alexander Sell, Nazanin Hoghooghi, Felix Rohde, Armin Zach, Wilhelm Kaenders
TOPTICA Photonics AG, Germany

We characterize a passively carrier envelope phase-stable Er:fiber difference frequency comb at 1550 nm. Phase noise of single comb lines over nearly an optical octave is measured via a delayed self-heterodyne beat of a cw clean-up laser. Repetition-rate stabilization achieves a RF-reference limited line-width. A lock to a low-noise optical reference shows Hz level out-of-loop line-widths. The measured phase noise is in excellent agreement with the elastic tape model with a fix point at zero frequency.

**C1L-B Caesium Frequency Standards P/L001**
**Chair Krzysztof Szymaniec**

**08:40 First Accuracy Evaluation of the METAS-FoCS2 Primary Frequency Standard #1069#**

Antoine Jallageas{2}, Laurent Devenoges{1}, Michael Petersen{2}, Laurent-Guy Bernier{1}, Jacques Morel{1}, Pierre Thomann{2}, Thomas Südmeyer{2}
{1}Institute of Metrology METAS, Switzerland; {2}Laboratoire Temps-Fréquence, Université de Neuchâtel, Switzerland

Microwave leakages induced by spurious surface currents were eliminated with the installation of a graphite cylinder around the free evolution zone in FoCS-2. This improvement is a significant step toward the full metrological evaluation. We present here the latest measurements for the residual microwave leakages, the collisional shift and the microwave cavity-related frequency shifts and a first uncertainty budget for FoCS-2 with a total uncertainty at the 10-15 level.

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**09:00 Improvements of the Statistical and Systematic Uncertainty Contributions of PTB's Fountain Clocks #1031#**

Stefan Weyers{3}, Vladislav Gerginov{3}, Michael Kazda{3}, Burghard Lipphardt{3}, Georgi Dobrev{2}, Kurt Gibble{1}
{1}Department of Physics, The Pennsylvania State University, United States; {2}Faculty of Physics, Sofia University, Bulgaria; {3}Physikalisch-Technische Bundesanstalt, Germany

For both PTB caesium fountain clocks CSF1 and CSF2 new systematic uncertainty evaluations have been undertaken. Particular attention has been concentrated on a more rigorous evaluation of frequency shifting effects due to microwave leakage, the distributed cavity phase and cold collisions. Because the necessary measurements for such investigations strongly benefit from improved frequency stability, an optically stabilized microwave source has been developed at PTB and now operates routinely. For the fountains we obtain overall systematic uncertainties at the low 10^-16 level. We will report about details of the setups and evaluations.

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**09:20 Development of a High Performance Optical Cesium Beam Clock for Ground Applications #1138#**

Patrick Berthoud, Manuel Haldimann, Christophe Ducommun, Frederic Lefebvre, Radoslav Pantic, Luc Schneller, Fabiano Kroll, Nicolas Voirol, Alain Michaud
Oscilloquartz SA, Switzerland

Oscilloquartz SA, Switzerland is developing a ground cesium beam clock for ground applications. Thanks to optical pumping rather than magnetic deflection, the useful atomic beam flux will be largely increased without compromising the clock lifetime. The aim is to get a transportable clock fitting in a standard frame (19” width, 3U high), providing an output signal frequency stability of 3E 12 t^-1/2 with a 10 years lifetime. Clock integration

results will be presented at the conference together with frequency stability measurements and a signal-to-noise budget analysis.

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**09:40 Towards an Engineering Model of Optical Space Cs Clock #1218#**

Roman Schmeissner{2}, Adel Douahi{2}, Isabelle Barbereau{2}, Philippe Dufreche{2}, Arnaud Brechenmacher{2}, Klaus Kudielka{1}, Frederic Loiseau{1}, Andreas Romer{1}, Christoph Roth{1}, Willem Coppoolse{1}, Nicole Mestre{2}, Michel Baldy{2}

{1}RUAG, Switzerland; {2}Thales Electron Devices, France

Thales Electron Devices and RUAG currently develop the engineering model of the Optical Space Cs Clock. Recent progress of the project is reported. Emphasis is put on the test and comparison of new laser sources, the implementation of an isolator free optics subsystem and the space evaluation of the laser and the photodiode.

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| **C1L-C** | **Low Noise Synthesis** | **P/L002** |
| **Chair** | **Mike Underhill** | |

**08:40 Suppressing Lo-Induced Instabilities in Passive Frequency Standards by Quantum Control (Invited) #1003#**

Michael Biercuk

University of Sydney, Australia

The physical correspondence between quantum bits and the atomic transitions employed in many passive frequency standards provides an opportunity to explore how new quantum control techniques designed to suppress qubit error for large-scale quantum information may be brought to bear in the precision metrology community. We report new theoretical developments in noise filtering and quantum state estimation and how they can be applied to the stabilization of passive frequency standards suffering from LO noise. We treat a range of system parameters but focus on the challenging case of LO noise that contains spectral weight near the inverse cycle time in the presence of large dead time. We experimentally demonstrate that embedding quantum optimal estimation techniques within the feedback loop of a Ytterbium-ion microwave standard can improve both correction accuracy and long-term stability (assuming a perfect atomic reference). Our experiments provide quantitative validation of our theoretical insights and suggest new "software-only" approaches to improve passive frequency standard performance in tight-SWAP applications where LO stability is performance limiting.

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**09:20 Frequency Synthesis from Cryogenic Sapphire Oscillator #1043#**

Etienne Vaillant{2}, Fabrice Sthal{2}, Joël Imbaud{2}, Christophe Fluhr{2}, Serge Grop{2}, Vincent Giordano{2}, Enrico Rubiola{2}, François-Xavier Esnault{1}, Gilles Cibiel{1}

{1}CNES, France; {2}FEMTO-ST, France

To characterize ultra-stable resonators, the passive technique with carrier suppression is used to measure the inherent phase stability of the ultra-stable resonators. This kind of bench usually uses both identical resonators inserted in each arm in order to suppress the noise of the source [2]. To operate with only one resonator, the driving source must have a phase noise lower than the best resonators that are measured. At 5 MHz, the power spectral density of phase fluctuations of these best quartz crystal resonators is expected around -140 dBc/Hz. In these conditions, the driving source cannot be an ultrastable 5 MHz quartz oscillator. Cryogenic sapphire oscillators present a very low phase noise [3]. Thus in this paper, first results of frequency synthesis chain from cryogenic sapphire oscillator are presented. A 100 MHz signal is divided until 5 MHz in order to get the best phase noise. Several divider combinations are presented and discussed. The limits of commercial dividers are shown and best results have been obtained using regenerative dividers (Fig. 1). Further investigations are proposed in order to improve these results.

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**09:40 A HBAR-Oscillator-Based 4.596 GHz Frequency Source: Design, Characterization and Application to a Cs Microcell Atomic Clock #1049#**

Rodolphe Boudot{2}, Gilles Martin{1}, Jean-Michel Friedt{1}
{1}FEMTO-ST, France; {2}FEMTO-ST - CNRS, France

This paper presents a HBAR-oscillator based 4.596 GHz frequency source. This source is used as a local oscillator in a CPT-based laboratory-prototype Cs vapor cell atomic clock.

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**10:00 Low Phase Noise 10MHz Crystal Oscillators #1234#**

Tsvetan Burtichelov, Jeremy Everard
University of York, United Kingdom

This paper describes the design and implementation of low phase noise 10MHz Crystal Oscillators which are being used as part of the chain of a local oscillator for use in compact atomic clocks. The design considerations and phase noise measurements are presented. This paper is based on a previous design [1] but now demonstrates significantly improved phase noise performance and now includes the key circuit descriptions. The latest measurements of the 10MHz crystal oscillator’s performance demonstrates a phase noise of -123dBc/Hz at 1 Hz and -148dBc/Hz at 10 Hz. The results compare well with the best 5MHz BVA oscillators when 6dB (÷2) is subtracted.

**C2L-A Lattice Clocks II P/X001**

**Chair Jérôme Lodewyck**

**10:50 Realization of a Timescale with an Optical Clock #1042#**

Christian Grebing, Ali Al-Masoudi, Sören Dörscher, Sebastian Häfner, Vladislav Gerginov, Stefan Weyers, Burghard Lipphardt, Fritz Riehle, Uwe Sterr, Christian Lisdat
Physikalisch-Technische Bundesanstalt, Germany

We demonstrate how PTB’s strontium lattice clock (overall availablity: ≈30%) in combination with a continuously running conventional maser flywheel is able to maintain a local timescale with a time error of less than 200 ps compared to an ideal reference over about 12 days, or 1.6 × 10^(−16) in fractional frequency. Thus, the optical timescale surpasses the performance of a timescale referenced to a continuously running primary clock by more than a factor of two.

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### 11:10 Months-Long Evaluation of Maser Frequency by a Lattice Clock Toward the Steering of Time Scales #1154#

Tetsuya Ido, Hidekazu Hachisu, Fumimaru Nakagawa, Yuko Hanado
NICT, Japan

With reference to a 87Sr lattice clock, the frequency of a hydrogen maser (HM) was evaluated intermittently for a few months. The result of the calibration was utilized for the most accurate TAI-based absolute frequency measurement of 10^-16 level. The result was also used for the feasibility study of "optical" steering of time scales. Taking account the calibration data as well as the record of the HM frequency stored in Japan Standard Time system, it is realized that calibrations by an optical clock once in two weeks are sufficient to maintain a HM-based time scale in a few ns level.

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### 11:30 Precise Frequency Comparison of Clocks Considering the Dead Time Uncertainty of Frequency Link #1161#

Takehiko Tanabe{1}, Daisuke Akamatsu{1}, Takumi Kobayashi{1}, Akifumi Takamizawa{1}, Shinya Yanagimachi{1}, Takeshi Ikegami{1}, Tomonari Suzuyama{1}, Hajime Inaba{1}, Sho Okubo{1}, Masami Yasuda{1}, Feng-Lei Hong{2}, Atsushi Onae{1}, Kazumoto Hosaka{1}
{1}National Metrology Institute of Japan (NMIJ), Japan; {2}Yokohama National University, Japan

We have developed Yb and Sr optical lattice clocks at NMIJ. So far the uncertainties of the absolute frequencies of the clock transitions were mainly limited by the uncertainty of a comparison with UTC(NMIJ). Recently, we carefully evaluate the uncertainties of the link between the Sr optical lattice clock and TAI via UTC(NMIJ) using a caesium fountain atomic clock located at NMIJ as a transfer oscillator. In this way, we could reduce the final uncertainty to one third that of our previous measurement.

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### 11:50 87Sr and 88Sr Optical Lattice Clocks at NPL #1163#

Ian Hill{1}, Richard Hobson{1}, William Bowden{1}, Marco Menchetti{1}, Antoine Rolland{1}, Fred Baynes{1}, Helen Margolis{1}, Patrick Baird{2}, Kai Bongs{3}, Patrick Gill{1}
{1}NPL, United Kingdom; {2}Oxford, United Kingdom; {3}University of Birmingham, United Kingdom

We present an evaluation of the NPL 87Sr optical lattice clock. The evaluation is aided by an improved stability of the clock, provided by an ultra-stable laser at 1064 nm delivered across a fibre comb-based transfer oscillator scheme to 698 nm. We also present progress towards an accurate 88Sr clock and show the elimination of probe induced shifts using a modified-hyper-Ramsey spectroscopy.

**12:10 Recent Advances in Precision Spectroscopy of Ultracold Atoms and Ions #1113#**

Alexey Taichenachev{1}, Valeriy Yudin{2}, Sergey Bagayev{1}
{1}Institute of laser physics SB RAS, Russia; {2}Novosibirsk State University, Russia

New methods and approaches in precision spectroscopy of ultracold atoms and ions are discussed with an emphasis on contributions of Institute of Laser Physics SB RAS.

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| **C2L-B** | **CPT Cell Standards** | **P/L001** |
| **Chair** | **Salvatore Micalizio** | |

**10:50 A High-Performance CPT-Based Cs Vapor Cell Atomic Clock Using Push-Pull Optical Pumping #1048#**

Moustafa Abdel Hafiz, Rodolphe Boudot
FEMTO-ST, France

This paper presents a high-performance CPT Cs vapor cell atomic clock using the push-pull optical pumping technique. A fractional frequency stability of 2 10^(-13) up to 100 s has been demnstrated. Latest results will be presented at the conference.

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**11:10 A Compact Double-Modulation Coherent Population Trapping Clock #1168#**

Peter Yun, Sinda Mejri, Francois Tricot, Emeric de Clercq, Stephane Guérandel
Observatoire de Paris, France

We demonstrate a setup for a high performance coherent population trapping (CPT) atomic clock based on the double-modulation scheme, i.e., the synchronous modulation of the light polarization and of the phase between the two components of the bichromatic laser beam. With the help of a current modulated DFB laser diode to generate the bichromatic beam and a liquid crystal polarization rotator to realize the polarization modulation, it is possible to implement a very compact, robust and high performance atomic clock.

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**11:30 Progress on the CPT Clock: Reduction of the Main Frequency Noise Sources #1139#**

Francois Tricot{2}, Sinda Mejri{2}, Peter Yun{2}, Bruno Francois{1}, Jean-Marie Danet{3}, Stephane Guerandel{2}, Emeric De Clercq{2}
{1}INRIM, Italy; {2}LNE-SYRTE, France; {3}SYRLINKS, France

Clocks based on coherent population trapping (CPT) represent promising candidates for on-board space and industrial applications thanks to their simple scheme and high stability performance. Indeed in our CPT clocks the microwave frequency is optically carried into a vapor cell of cesium. We present here the main frequency noise sources for the clock stability, now σy (1s) = 3.2x10-13; and what we are doing to decrease the frequency noise contributions.

**11:50 Back Ground Noise Suppression in CPT Based Atomic Clock by Differential Detection #1017#**

Huifang Lin{1}, Bozhong Tan{2}, Yuan Tian{2}, Sihong Gu{2}
{1}Huazhong University of Science and Technology, China; {2}Wuhan Institute of Physics and Mathematics,Chinese Academy of Sciences, China

The conventional CPT atomic clock uses VCSEL as the light source, and the obtained CPT signal is with strong background noise which deteriorates frequency stability of the clock. We present a scheme which extracts Faraday effect CPT signal by means of differential detection technique. The strong background noise can be considerably depressed and our experimental study result reveals that it is promising to improve frequency stability by two orders of magnitudes compared with the conventional scheme, at same time the size and power consumption of the CPT atomic clock can be kept at the same level.

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**12:10 Investigation of High SNR Ramsey Spectrum with Dispersion Detection in the CPT Atomic Clocks #1172#**

Xiaolin Sun, Pengfei Cheng, Chi Xu, Jianwei Zhang, Lu Zhao, Lijun Wang
Tsinghua University, China

The lin-par-lin Ramsey coherent population trapping 87Rb clock using dispersion detection technique has a promising performance. We theoretically and experimentally investigate the signal-to-noise ratio of the Ramsey spectrum signal by varying the relative angle of the polarizer and analyzer as well as the magnetic field. Based on the experimental results, the optimized relative angle and magnetic field are determined. This kind of atomic clock is attractive for the development of high performance and compact vapor clock based on CPT.

| **C2L-C** | **Opto-electronics and Microwave Oscillators** | **P/L002** |
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| **Chair** | **Gilles Cibiel** | |

**10:50 Photonic Oscillators: Beyond the State of the Art (Invited) #1196#**

Lute Maleki
OEwaves, Inc., United States

Photonic oscillators are based on generation of RF (microwave/mm-wave) signals by beating equally spaced coherent harmonics of light produced by one, or multiple lasers on a fast photodiode. The frequency of the RF signal corresponds to the equally spaced interval between the harmonics, and thus it can be readily selectable. The phase noise of the RF signal corre-sponds to the phase noise of the optical signal that generated it.

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**11:30 Low Phase Noise 10GHz Bragg Resonator Oscillator #1229#**

Pratik Deshpande, Simon Bale, Jeremy Everard
University of York, United Kingdom

This paper describes the theory and design of a 10GHz low noise oscillator which uses a Bragg resonator. The resonator utilizes an aperiodic arrangement of low loss alumina plates mounted in a cylindrical metal waveguide (Resonator Q0 ~ 200,000). The oscillator demonstrates a phase noise performance of -123 dBc/Hz at 1kHz offset and -153 dBc/Hz at

10kHz offset. Extensive optimization of different transistors operating at different power levels has taken place. The gain, noise figure and residual phase noise of these amplifiers is reported. This enables a suitable choice for a given oscillator frequency. The power requirements are 6V at 52mA.

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**11:50 Brillouin Scattering in a Lithium Fluoride Crystalline Resonator for Microwave Generation #1235#**

Souleymane Diallo, Guoping Lin, Jean Pierre Aubry, Yanne K. Chembo
Femto-ST Institute, France

We report Brillouin lasing in a monofluoride crystalline resonator for the very first time. While Raman scattering results from the interaction between a laser beam and an optical phonon providing a frequency shift in the THz range, Brillouin scattering results from the interaction between a strong laser beam and an acoustic phonon leading to a frequency shift of few GHz, which makes it more suitable for microwave generation. We present a time domain model which tracks the dynamics of the Stokes and pump waves and finally, with the help of a stability analysis, we determine analytically the threshold power. Such a laser has great potential for ultra-pure microwave and multi-wavelength generation.

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**12:10 Ultra-Low-Noise Optoelectronic Oscillator at 10 GHz Based on a Short Fiber Delay #1204#**

Oriane Lelièvre{3}, Vincent Crozatier{3}, Ghaya Baili{3}, Perrine Berger{3}, Loic Morvan{3}, Grégoire Pillet{3}, Daniel Dolfi{3}, Olivier Llopis{2}, Fabienne Goldfarb{1}, Fabien Bretenaker{1}
{1}Laboratoire Aimé Cotton, CNRS, France; {2}Laboratoire d'Analyse et d'Architecture des Systèmes, CNRS, France; {3}Thales Research and Technology, France

We report on an optoelectronic oscillator (OEO) at 10 GHz based on a single 1 km long fiber delay, and exhibiting simultaneously an ultra-low close-in phase noise ( 94 dBc/Hz @100 Hz) and a low spurious level (below -110 dBc/Hz). These results are well predicted by a model taking into account the frequency and intensity noise from the laser source that are converted into phase noise.

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| **C3L-A** | **Optical Oscillators and Spectroscopy** | **P/X001** |
| **Chair** | **Thomas Südmeyer** | |

**14:00 Direct Comparison of Two Optical Cryogenic Silicon Resonators #1216#**

Dan Gheorghita Matei{2}, Thomas Legero{2}, Wei Zhang{1}, Robin Weyrich{2}, Christian Grebing{2}, Sebastian Häfner{2}, Christian Lisdat{2}, Fritz Riehle{2}, Lindsay Sonderhouse{1}, John Michael Robinson{1}, Jun Ye{1}, Uwe Sterr{2}
{1}JILA, United States; {2}Physikalisch-Technische Bundesanstalt, Germany

We discuss the fundamental and technical limits to the stability of an optical resonator made of single-crystal silicon. By directly comparing two identical systems we measure the effect of seismic perturbations, residual amplitude modulation, temperature stability and vacuum pressure fluctuations on the overall stability. We present the measures taken to reduce their influence below the thermal noise limit.

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### 14:20 Temperature and Current Dependence of 1/F Frequency Noise in Narrow-Linewidth Discrete-Mode Lasers #1090#

Stefan Kundermann{1}, John O'Carroll{2}, Diarmuid Byrne{2}, Lina Maigyte{2}, Brian Kelly{2}, Richard Phelan{2}, Dmitri L. Boiko{1}
{1}CSEM, Switzerland; {2}Eblana Photonics Ltd, Ireland

Wavelength tunable lasers for coherent optical communications systems and atomic spectroscopy need to meet stringent requirements on narrow linewidth emission. For the majority of semiconductor lasers, the integral noise features such as the linewidth and RIN are defined by flicker (1/f) noise contribution, which is believed to be due to generation-recombination processes through recombination centers in defects (e.g. dislocations). In this talk we will report on 1/f noise dependence on the cavity length as well as driving current and temperature of the narrow linewidth Discrete Mode Laser Diodes (DMLD) and discuss the possible origin of these effects.

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### 14:40 Efficient Frequency Tripling of a Telecom Laser Diode Stabilized to Iodine Line at 515 nm in the 10^-14 Range #1178#

Charles Philippe{1}, Rodolphe Le Targat{1}, Frédéric Du Burck{2}, Ouali Acef{1}
{1}Observatoire de Paris - SYRTE, France; {2}Université Paris 13-Sorbonne Paris - LPL, France

Molecular iodine represents one of the most interesting atomic references for the realization of a frequency standard in the range of telecom laser wavelength. We have developed effective, compact and original third harmonic generation setup delivering up to 300 mW of green radiation at 514 nm with an optical conversion efficiency of P3w/Pw ~36%. Well known frequency modulation transfer is used to interrogate molecular iodine, in a compact laboratory optical setup. A preliminary evaluation of the frequency stability is reported as Sigma(y)(Tau) = 6.10^(-14) Tau^(-1/2).

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### 15:00 Phase Locking an Atom Interferometer #1149#

Andrea Bertoldi{3}, Ralf Kohlhaas{4}, Etienne Cantin{3}, Alain Aspect{1}, Arnaud Landragin{2}, Philippe Bouyer{3}
{1}IOGS, France; {2}LNE - SYRTE, France; {3}LP2N - IOGS, France; {4}SRON Netherlands Institute for Space Research, Netherlands

In atom interferometry the phase evolution of a quantum superposition state is measured with respect to a reference signal. The measurement has a limited unambiguous interval, since not the phase but its projection is measured as a population unbalance on two energetic levels. Resolving phase wrapping brings to a longer interrogation interval and hence instrument sensitivity. We extended the unambiguous probe interval using coherence preserving measurements and phase corrections, and demonstrated the phase lock of the

clock oscillator to an atomic superposition state. On this basis we implemented a protocol to improve atomic clocks limited by local oscillator noise.

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### 15:20 Absolute Frequency of the Inter-Combination Line in 171Yb with Use of the Clock Transition #1023#

Liam Salter, John McFerran
University of Western Australia, Australia

We report on the absolute frequency measurement of the 6s2 1S0 (F=1/2) - 6s6p 3P1 (F=3/2) transition in 171Yb. Knowledge of this frequency will aid those searching for the 1S0 (F=1/2) - 3P0 (F=1/2) clock transition without access to highly accurate frequency standards. The mean frequency is 539 390 405 430 (190) (16) kHz. An absolute frequency for the same line can be inferred from a result in Pandey et al, PRA, 80, 022518, 2009. We find our frequency to be higher by 39.4MHz. We are unable to resolve the 171Yb (F=1/2-3/2) and 173Yb (F=5/2-3/2) lines, which have previously been reported to be closer than 2MHz. The latter we estimate to be weaker in strength by approximately a factor of ten.

## C3L-B Optical Fibre Frequency Transfer P/L001

**Chair Paul-Eric Pottie**

### 14:00 Validating Frequency Transfer via a Stabilised Fibre Link for Optical Clock Comparisons #1187#

Sebastian Koke, Christian Grebing, Alexander Kuhl, Gesine Grosche
Physikalisch-Technische Bundesanstalt (PTB), Germany

Comparisons of remote optical clocks with uncertainty ~1E-18 require careful validation of the frequency transfer carried out via phase-stabilised fibre links connecting them. This differs from assessing the performance of the link itself. Here, we present link data analysis, validation and selection in a recent comparison of two Sr clocks located at SYRTE and at PTB separated by 700 km line-of-sight. Using a looped link set-up, we validate each 1000s data segment requiring that the frequency offset is below 5E-18 (5sigma). The overall uncertainty contribution of the fibre link is two orders of magnitude below the uncertainty of the clocks.

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### 14:20 Towards an International Optical Clock Comparison Between NPL and SYRTE Using an Optical Fiber Network #1035#

J. Kronjäger{4}, G. Marra{4}, O. Lopez{2}, N. Quintin{2}, A. Amy-Klein{2}, W. Lee{1}, P. Pottie{3}, H. Schnatz{5}
{1}Korea Research Institute of Standards and Science, Korea, South; {2}Laboratoire de Physique des Lasers, France; {3}Laboratoire National de Métrologie et d'Essais–Système de Références Temps-Espace, France; {4}National Physical Laboratory, United Kingdom; {5}Physikalisch-Technische Bundesanstalt, Germany

We aim at performing an international comparison of the optical clocks developed at SYRTE and NPL using optical frequency transfer through a long haul fiber link between London and Paris. Our experimental setup employs a novel hybrid topology combining active compensation and two-way technology, and a new implementation using a repeater laser

station at the pivot point. We present a characterization of the residual phase noise using loop-back measurements over the fiber pair and demonstrate ultra-stable laser comparisons between NPL and SYRTE. Together with the link between France and Germany, the London-Paris link will allow simultaneous multiple clock comparisons.

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### 14:40 Transfer of Stable Optical Frequency for Sensory Networks via 306 km Optical Fiber Link #1152#

Martin Cizek{2}, Lenka Pravdova{2}, Vaclav Hucl{2}, Simon Rerucha{2}, Jan Hrabina{2}, Bretislav Mikel{2}, Vladimir Smotlacha{1}, Josef Vojtech{1}, Josef Lazar{2}, Ondrej Cip{2}
{1}CESNET, z. s. p. o., Czech Rep.; {2}Institute of Scientific Instruments of the CAS, Czech Rep.

The remote calibration of interrogators of Fiber Bragg Grating strain sensory networks may be one of future industrial applications employing highly-stable optical frequency dissemination from optical frequency standards. We present a 306 km long optical fiber link established in the Czech Republic where a coherent transfer of a stable optical frequency has been demonstrated. The link between ISI CAS Brno and CESNET Prague uses an internet communication fiber where a DWDM window of 1540-1546 nm is dedicated for the coherent transfer and 1PPS signal. The link is equipped with 6 bidirectional EDFA amplifiers. The optical frequency standard at 1540.5 nm is used for the coherent transfer where compensation with AOM of the Doppler shift induced by the optical fiber is done. The output frequency of the VCO driving the AOM is continuously measured and logged by a RF counter for computing changes in the transport delay introduced by external influences on the optical line. To compare with a different measuring method a setup for analysing the transport delay of a 1 PPS signal is connected to the same DWDM mux/demux at both sides. This comparison is a subject of results of the paper.

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### 15:00 Absolute Frequency Measurement of the 173Yb Clock Transition via a 642-km Fiber Link #1115#

Cecilia Clivati{2}, Giacomo Cappellini{6}, Lorenzo Livi{6}, Francesco Poggiali{6}, Mario Siciliani de Cumis{3}, Marco Mancini{7}, Guido Pagano{7}, Matteo Frittelli{2}, Alberto Mura{2}, Giovanni Costanzo{4}, Filippo Levi{2}, Davide Calonico{2}, Leonardo Fallani{8}, Jacopo Catani{1}, Massimo Inguscio{5}
{1}INO-CNR, LENS, Italy; {2}INRIM, Italy; {3}INRIM, INO-CNR, Italy; {4}INRIM, Politecnico di Torino, Italy; {5}INRIM, University of Florence, LENS, Italy; {6}LENS, Italy; {7}University of Florence, Italy; {8}University of Florence, LENS, Italy

We report on high-precision frequency measurement of the 173Yb clock transition using a long-haul optical fiber link. We transfer a narrow-linewidth telecom laser along 642 km of optical fiber and use it as a remote frequency reference for long-term, SI-traceable spectroscopy of an ultracold gas of 173Yb. Our results improve the accuracy reported in literature by two orders of magnitude and demonstrate the link as a tool for high-precision spectroscopy at a level which cannot be obtained with standard techniques.

**15:20 Geodetic VLBI Field-Test of Lift: a 550 km Long Optical Fiber Link for Remote Antenna Synchronization #1181#**

Davide Calonico{2}, Cecilia Clivati{2}, Matteo Frittelli{2}, Alberto Mura{2}, Filippo Levi{2}, Massimo Zucco{2}, Federico Perini{1}, Claudio Bortolotti{1}, Mauro Roma{1}, Roberto Ambrosini{1}, Giuseppe Maccaferri{1}, Monia Negusini{1}, Matteo Stagni{1}, Mauro Nanni{1}, Alessandra Bertarini{3}
{1}INAF - Osservatorio di Radioastronomia, Italy; {2}INRIM, Italy; {3}Institut für Geodäsie und Geoinformation der Universität Bonn, Germany

We present a geodetic VLBI field-test of LIFT, the Italian fiber link. In September 2015, the Medicina VLBI antenna participated to the Eur137 experiment, in tag along mode, using as reference systems both the local H maser and a remote H maser hosted at the INRIM labs in Turin, disseminated to Medicina via a 550 km fiber link. We describe the set-up, the measurement campaign, the results and their analysis togerther wwith the perspectives of the activity.

| **C3L-C** | **Microwave Frequency Standards** | **P/L002** |
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| **Chair** | **Christoph Affolderbach** | |

**14:00 Main Features of Space Rubidium Atomic Frequency Standard for BeiDou Satellites (Invited) #1110#**

Ganghua Mei, Da Zhong, Shaofeng An, Feng Zhao, Feng Qi, Fang Wang, Gang Ming, Wenbin Li, Pengfei Wang
Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, China

Wuhan Institute of Physics and Mathematics (WIPM), Chinese Academy of Sciences has been developing the space borne rubidium atomic frequency standard (RAFS) for BeiDou navigation satellite system since late 1990's. The day frequency stability of the RAFS's employed in Bei-Dou regional system is within 2~5×10-14. A new prototype of RAFS developed for BeiDou glob-al system has been realized, and a day frequency stability of 3×10-15, obtained, In this paper we outline main features of the space RAFS designed by WIPM.

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**14:40 Relaxation Time Measurements in a Rb Vapor Cell #1102#**

Mohammadreza Gharavipour{2}, Ivan S. Radojicic{1}, Florian Gruet{2}, Christoph Affolderbach{2}, Aleksandar J. Krmpot{1}, Brana M. Jelenkovic{1}, Gaetano Mileti{2}
{1}Institute of Physics, University of Belgrade, Serbia; {2}Laboratoire Temps-Fréquence, Institut de Physique, Université de Neuchâtel, Switzerland

We are studying the physics of compact atomic frequency standards (atomic clocks) based on Rb vapor cells, in view of the development of novel high-performance atomic clocks for ap-plications such as satellite navigation systems or industrial metrology applications. Here we report on measurements of the T1 and T2 relaxation times in the Rb vapor cell of our clock, using and comparing several different methods such as relaxation in the dark, Ramsey scheme, and continuous-wave laser-microwave double resonance.

**15:00 Precision Test of the ac-Stark Shift in a Vapor-Phase System #1071#**

Salvatore Micalizio{2}, James Camparo{1}, Filippo Levi{2}, Bruno Francois{2}, Claudio Eligio Calosso{2}, Aldo Godone{2}
{1}Aerospace Corporation, United States; {2}INRIM, Italy

In this work, we present a new methodology for measuring the ac-Stark shift in a Rb cell with a high level of accuracy. Specifically, we take advantage of the pulsed optical pumping technique and of the Ramsey interaction scheme. A low power perturbing laser pulse tuned to the D1 absorption resonance is applied to the atoms during their free evolution phase. In this way we were able to verify the AC Stark shift theory for a perturbing laser tuned over a broad optical frequency range (18 GHz). In our experiments we test both the frequency dependence of the scalar and, for the first time, tensor components of the light shift.

# Satellite Workshop, Friday 8th April

**P/L001 Lectures**

**P/L005 Posters**

## Optical clocks: quantum engineering and international timekeeping

The workshop is organised by two EMRP project consortia: International timescales with optical clocks (ITOC) and Quantum Engineered States for Optical Clocks and Atomic Sensors (QESOCAS). Complementing the scientific programme of EFTF, it will address recent developments related to the use of quantum engineered states to enhance the stability of optical clocks, as well as progress made towards using optical clocks for international timekeeping. Two invited talks from leading experts in the field will be followed by presentations from members of the two project consortia. Poster presentations from all participants are welcomed for the afternoon session.

| | |
|---|---|
| 8:30 - 09:00 | Registration |
| 09:00 - 09:45 | **Fritz Riehle, PTB**<br>'Towards a redefinition of the SI second by optical clocks: achievements and challenges' |
| 09:45 - 10:30 | **Augusto Smerzi, Istituto Nazionale di Ottica, Trento**<br>'Witnessing entanglement with the Fisher information: from metrology to Bell nonlocality' |
| 10:30 - 11:00 | Coffee / tea break |
| 11:00 - 11:30 | **Helen Margolis, NPL**<br>'Overview of ITOC project' |
| 11:30 - 12:00 | **Sébastien Bize, LNE-SYRTE**<br>'Overview of QESOCAS project' |
| 12:00 - 12:30 | ITOC highlight talk |
| 12:30 - 13:00 | QESOCAS highlight talk |
| 13:00 - 14:00 | Lunch break |
| 14:00 - 16:00 | Posters |
| 16:00 | End of meeting |

Contact Person: Helen Margolis (NPL)

Organising committee: Helen Margolis (NPL, UK), Sébastien Bize (LNE-SYRTE, France), Davide Calonico (INRIM, Italy), Christian Lisdat (PTB, Germany).

# Authors Index

# Exhibitors

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Noise XT is one of the most experienced company in the world regarding Phase Noise. Being about frequency synthesizers or Phase Noise analyzers, our expertise can certainly help you achieve performance goals or solve issues.

Since 1992, our continuous innovation on low phase noise design made us the highest performance provider on the market. Our customers are typically in the Defense, Space, Telecommunication or Time and Frequency community. http://www.noisext.com/ Stand 2

GuideTech's newest product-line includes the **GT9000,** scalable from 2 to 24 channel "CTIA" Continuous Time Interval Analyzer & "TIC" Time Interval Counter with Integrated 3D touch screen display, **GT9001P-USB3,** a 2 channel Portable "CTIA" & "TIC" USB3 controlled, **GT9000R,** 19" Rack-Mount scalable from 2 to 24 channel "CTIA" & "TIC". Since 1988, A world leader in the design, development and manufacturing of High-Precision 0.9pS resolution, 4M m/s, Zero dead time Continuous Time & Frequency measurement instruments for Scientific Laboratories, Research and Automated Test Applications. GuideTech's products are used in commercial, education, research, government and military systems/applications worldwide.

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SpectraDynamics, Inc. (SDI) is a Colorado, USA-based company. Founded in 1994, specializing in high performance time and frequency distribution systems. In association with the National Institute of Standards and Technology, SpectraDynamics participates in the research and development of technology to provide the low noise electronics needed to support atomic time and frequency standards.

SpectraDynamics main products are Time and Frequency Distribution Amplifiers and Low Noise Frequency Synthesizers. Our featured items are the HROG series, high performance frequency and phase micro-steppers with under 1 fs resolution, and the HPDA-15RMi series, ultra low noise frequency distribution amplifiers. In addition to the standard products, SpectraDynamics has the ability to deliver custom solutions engineered to meet your specific needs.

http://www.spectradynamics.com/ Stand 4

For more than 80 years, Rohde & Schwarz has stood for quality, precision and innovation in all fields of wireless communications. The privately owned company is strategically based on four pillars: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. The electronics group, headquartered in Munich (Germany), has a global presence and is among the world market leaders in all of its business fields.

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Laser Quantum is a world-class manufacturer of revolutionary solid-state and ultrafast laser systems. Our products lead the industry in performance specifications, reliability, compactness and operational lifetime. They have been used in ground-breaking research, and continue to push the boundaries of science. You will find Laser Quantum lasers in laboratories worldwide and used in diverse applications including attosecond physics, forensics and genomics due to the wide range of wavelengths and powers we offer. Our wealth of experience, together with our passionate team, mean we are committed to providing you with a service and laser system that exceeds your expectations.

We have recently launched our first complete 1GHz frequency comb, an exceptional supercontinuum typ.1uW per mode with easy access to VIS and NIR ranges, and will be showcasing its capabilities at the European Time and Frequency Forum. For more information, please visit our website:

www.laserquantum.com Stand 6

M Squared Lasers research, design and manufacture world-class lasers and advanced photonic systems for use in a myriad of academic, commercial and industrial applications. Its high performance systems are critical enablers in fundamental physics research and behind a number of 'world firsts' from the first demonstration of 'teleportation' to the first stable ultra-cold molecules. Its technology is also being used to enable advances in the commercial world, most recently in the detection and classification of gases in the oil and gas industry and threat detection for the security sector.

Constantly covering new ground, M Squared is dedicated to innovation, actively involved in collaborative research projects and working on next generation quantum technologies. Founded in 2006, by laser experts Dr Graeme Malcolm, OBE and Dr Gareth Maker, the company is now considered a leader in its field.
http://www.m2lasers.com/ Stand 7

MOG Laboratories Pty Ltd (MOGLabs) offers tunable cateye and Littrow lasers, laser electronics, optical amplifiers, RF-synthesizers, AOM drivers and sub-picometer wavemeters. We develop scientific instrumentation from a user perspective, aimed at being a pleasure to use with performance to meet your expectations. We support our products, with a solid guarantee: we don't want unhappy customers.

MOGLabs is an offshoot of an experimental atom optics laboratory at the University of Melbourne. MOGLabs Europe based in Berlin was opened in 2012.

We are a company of in-the-lab scientists and engineers, people that know what you need because they've come from labs like yours. We bring you products which balance outstanding performance, superb features, high-quality design, excellent ergonomics and moderate cost.

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Lange Electronic GmbH, founded in 1977, develops, manufactures and distributes high precision time & frequency systems worldwide.

Besides this we represent the Positioning Technology branch of Spirent Communications Plc. in the field of GNSS simulation, Masterclock (precision timing and network synchronisation solutions) and Oktal-SE, a leading mathematical company doing 3D simulation via ray-tracing and several other methods in the areas of RF and radar simulation.

Our products are used in aerospace and on board of ships, in scientific experiments, in time laboratories and testing facilities e. g. the Aviation Gate in Braunschweig as well as in banks and insurance companies. The products on display are found in research and science as well as in development and testing of GNSS receivers/systems.

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Microsemi, the world leader in precise time solutions, sets the world's standard for time by offering solutions to generate , distribute and apply precise time for communications, aerospace/defence, IT infrastructure and metrology industries. Customers use Microsemi's advanced timing algorithms, atomic clocks and frequency reference technologies to build more reliable and highly efficient networks.

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Excitement is not measureable. Light is.

Menlo Systems, a leading developer and global supplier of instrumentation for high-precision metrology, was founded in 2001 as a spin-off of the Max Planck Institute for Quantum Optics, with the foremost aim to commercialize optical measurement technologies and make it available to newly emerging application fields. Menlo Systems maintains a strong bond to co-founder Theodor W. Hänsch, who pioneered precision laser techniques.

Known for the Nobel Prize-winning optical frequency comb technology, the Munich-based company offers complete solutions based on ultrafast lasers and synchronization electronics. Applications for our products and solutions span from research laboratories to truly industrial tasks. The patented technology is recognized by global laser manufacturers to whom we deliver OEM solutions for integration into cutting-edge products.

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Muquans is a young company who project consists in developing a new generation of high precision instruments based on laser trapping/cooling/manipulation of cold atoms.

Muquans is working on the development of the flowing products:

-An absolute quantum gravimeter capable of measuring gravity with a relative accuracy of 10^-9, dedicated to various applications in geophysics.

-An atomic clock, which provides time reference signal offering relative stability and accuracy close to 10^-15 and dedicated to time metrology applications.

- Integrated laser systems dedicated to trapping/cooling/manipulation of Rubidium atoms.

Muquans is a spin-off from two academic laboratories (LP2N and SYRTE) specialised in high precision measurements based on quantum manipulation of cold atoms. The technology developed by Muquans therefore benefits from all the experience and know how resulting from more than 15 years of academic research.

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For over seventy years, SAES Group has been the leading supplier of UHV and XHV solutions based on the Non-Evaporative Getter (NEG) technology for a variety of industrial and research applications. These solutions include compact NEG pumps with a large pumping speed for active atmospheric gases and, in particular, hydrogen, without generating vibrations or magnetic fields. In 2011, SAES Group introduced the PATENTED NEXTorr® pump, a revolutionary product that combines the NEG and sputtering ion pump technologies on one single flange. These pumps are widely used in a variety of UHV and XHV systems, particularly in the Atom Trap segment and in atomic clocks.

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TOPTICA is the world leader in diode laser and ultrafast technology for industrial and scientific markets. We offer the widest range of single mode tunable light in the 190 to 2900 nm and 0.1 to 2.7 THz spectral region with various accessories to measure, characterize, stabilize and analyze light. We recently extended this portfolio by introducing a frequency comb based on difference frequency generation.

A key point of the company philosophy is the close cooperation between development and research to meet our customers' demanding requirements for sophisticated customized system solutions and their subsequent commercialization.

TOPTICA is an active partner in clock-related projects: SOC2 - Space Optical Clocks, QTea - Quantum Technology Sensors and Applications and nuClock - Nuclear Clock with Thorium.

With our Passion for Precision, TOPTICA delivers!

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Stable Laser Systems is the premier provider of laser frequency stabilization hardware, systems, and accessories. Our expertise is the production and dissemination of Hz-level linewidths and low frequency drift. Our mounting and temperature control of high-finesse Fabry-Perot cavities provides high-performance, off-the-shelf solutions that can save hundreds of hours in the design and setup of narrow frequency and low-drift laser systems. Drawing on decades of combined expertise and research in laser frequency stabilization, we can assist you in choosing and characterizing the right cavity, provide you with an optimized mount and vacuum housing (including customized temperature controllers), as well as fiber-to-cavity coupling optics and associated electronics and services.

Our close partnership with Advanced Thin Films allows us to design matched housings for their world-class cavities. We also offer turnkey frequency stabilized laser systems based on high quality lasers, both at standard wavelengths and customized to your application. Our complete systems reliably deliver exceptional performance without compromising ease of use. Whether you need 1 Hz linewidth in the laboratory, or 1 kHz in the field, we can help you get there (and stay there) quickly.

http://www.stablelasers.com/ Stand 15

TimeTech GmbH was set up in 1990 as a spin off from the University of Stuttgart's Institute for Navigation. The team here specialises in intercontinental time transfer and very precise satellite positioning services.

TimeTech is a reliable provider of high-tech space systems and ground stations equipment and instruments for precise frequency and time transfer. TimeTech is mainly export-oriented with customers in Europe, North America, Asia and Australia. TimeTech's business areas are subdivided into project Business and Products. Since November 2012, TimeTech has embarked upon providing systematic and regular two-way link calibration service to our customers primarily the national metrological laboratories.

Project business encompasses scientific studies as well as hardware projects, related to Galileo, Aces, Rosetta, Venus Express and other space projects and ground stations. The Product Business takes care of development, production, testing and installing equipment and complex systems for orbit determination and positioning as well as high precision synchronization and transmission of time and frequency.
http://www.timetech.de/ Stand 16

Piktime Systems – satellite techniques and precise time sector company, established in 2007.

We concentrate on development and manufacturing equipment for precise, long-distance atomic clocks comparison.
We are a worldwide leader in our field.
What we do:

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- Development of time based products and services (navigation, security, data and document exchange, time stamping),
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- Time & frequency software and algorithms,
- Time & frequency counters and generators,
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Founded in 2006 in Neuchatel, Switzerland, T4Science is a leading designer and manufacturer of a full range of advanced, cost-effective and high-performance maser clock solutions. Its products are used in a wide variety of scientific applications and in the time and frequency industry.

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We offer a complete set of first-class services over the product lifecycle for total customer satisfaction. These services include: Supply & Installation, Training, Remote & On-Site Maintenance and On-Site Support.

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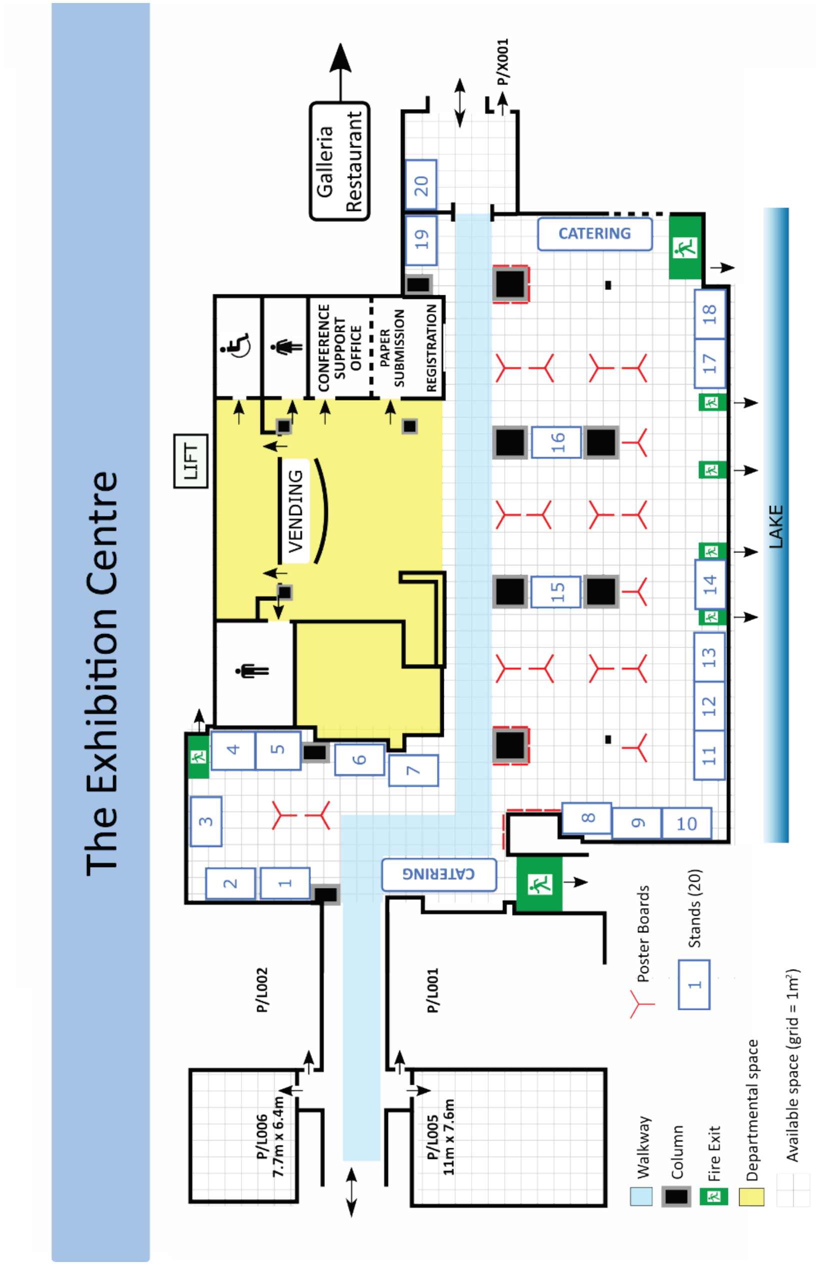
# Exhibition Centre Map



# 2017 Joint Conference of the European Frequency and Time Forum & IEEE International Frequency Control Symposium

## *July 9–13, 2017*

## *Micropolis, Besançon, France*

EFTF and IFCS are pleased to announce that the next joint conference of their long-established cooperation will take place at Micropolis, Besançon, the city that hosted the first European Frequency and Time Forum in 1987 and the first joint conference EFTF-IFCS in 1999. Micropolis Convention Center is now connected to Besançon historic downtown by a direct line of modern tramway and offers all equipment and amenities to host the plenary and parallel sessions of this new exciting event.

Lute Maleki and Bernard Dulmet will be the General Co-Chairs of the 2017 Joint Conference. Elizabeth Donley and Jérôme Delporte will be the Technical Program Co-Chairs. The Joint Program Committee will gather valued scientists from EFTF and IFCS Scientific Committee. The topics of the Conference will cover the following areas:

Group 1: Materials, Filters, and Resonators

Group 2: Oscillators, Synthesizers, Noise, and Circuit Techniques

Group 3: Microwave Frequency Standards

Group 4: Sensors and Transducers,

Group 5: Timekeeping, Time and Frequency Transfer, GNSS and Applications

Group 6: Optical Frequency Standards.

We expect the Conference Website eftf-ifcs2017.org to be on line by July 2016, with the first Call for papers to be issued by November 2016. Please consider submitting your abstracts by February 2017.

All members of Local Organizing Committee, brought together under the banner of The Société Française des Microtechniques et de Chronométrie, are eager to welcome you to renew the success of the two previous EFTF-IFCS Joint Meetings held in our city.

Notes:

# The method of establishing and maintaining the interstellar time reference during autonomous operation of satellites

WANG Xiang-lei，ZHAO Wen-jun

Beijing Satellite Navigation Center, 100094, BEIJING, CHINA

Email:chxywxl@163.com

As important national information and strategy infrastructure, GNSS has become one of the symbols of the national or political union's comprehensive political, economic and military strength, but also the important symbol of the comprehensive national power. GNSS is of great economic and social significance for national economy, public security and national defense construction and so on. In addition, as a kind of basic strategic resources, GNSS has quite important strategic position in modern wars.

In fact, GNSS is the time synchronization system, and system time reference is the key factors affecting the precision of positioning and timing. Moreover the system time reference with stead short-term stability is needed to broadcast ephemeris, clock error, ephemeris prediction etc to meet the real-time capability of time system.

Due to various limits, navigation satellite may lose the control of ground station in some cases (such as wars). In order to improve the system survivability, stability and synchronism, the autonomous punctuality is quite important for time reference.

Satellite clock is vulnerable to be influenced by various environmental factors such as temperature, ionosphere, and magnetic field, which makes satellite clock prone to abnormal value. Therefore, when establishing the interstellar time reference for autonomous operation of satellites, the Kalman filter should be introduced to eliminate the abnormal value and provide health data.

During autonomous operation of satellites because of some cases (such as wars), interstellar time reference for autonomous operation of satellites should be established and maintained to improve the system survivability and maintain system high precision stability.

For establishing and maintaining the interstellar time reference based on autonomous operation of satellites, this paper propose that first detecting, rejecting and repairing outliers with the Kaman algorithm in real time, then using the repaired GPS satellite clock bias to establish the time scale with the KPW algorithm. It is found that the interstellar time reference has a good long-term stability and short-term stability, which established with the above method by experiments.

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# Suppressing LO-induced instabilities in passive frequency standards by quantum control

A/Professor Michael Biercuk

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Abstract:

The physical correspondence between quantum bits and the atomic transitions employed in many passive frequency standards provides an opportunity to explore how new quantum control techniques designed to suppress qubit error for large-scale quantum information may be brought to bear in the precision metrology community.  We report new theoretical developments in noise filtering and quantum state estimation and how they can be applied to the stabilization of passive frequency standards suffering from LO noise.  We treat a range of system parameters but focus on the challenging case of LO noise that contains spectral weight near the inverse cycle time in the presence of large dead time.  We experimentally demonstrate that embedding quantum optimal estimation techniques within the feedback loop of a Ytterbium-ion microwave standard can improve both correction accuracy and long-term stability (assuming a perfect atomic reference).  Our experiments provide quantitative validation of our theoretical insights and suggest new "software-only" approaches to improve passive frequency standard performance in tight-SWAP applications where LO stability is performance limiting.

# 2D MOT vacuum chamber based on Zerodur


Sin Hyuk Yim[1], Tae Hyun Kim[1], Sangkyung Lee[1], Heesook Roh[1], Kyu Min Shim[1], Taeg Yong Kwon[2], Sang Eon Park[2], Sang-Bum Lee[2]

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We construct a vacuum chamber for 2-dimensional magneto-optical trap (2D MOT) [1] based on Zerodur block for producing slow atomic beam [2]. The surfaces of the Zerodur blocks are precisely polished using Mirek E10 abradant so that each blocks are optically contacted to compose the vacuum chamber. The electrical feedthroughs are soldered to the Zerodur block with Ti power. Rb dispenser and getter pump are connected to the electrical feedthroughs using laser spot welding. After baking the vacuum chamber around 100 ℃, the vapor pressure inside the vacuum chamber is below $10^{-8}$ Torr which is enough for cold atom experiment.

We use Rb87 as an atom source for 2D MOT and DBR lasers as light sources for cooling, repumping, and detecting, respectively. The modulation transfer spectroscopy (MTS) is employed to stabilize the frequency of the DBR laser [3]. The transition of $5S_{1/2}$,F=2 to $5P_{3/2}$,F'=3 is used for cooling and trapping the atoms with the cycling transition. The repumping laser is stabilized to the transition of $5S_{1/2}$,F=1 to $5P_{3/2}$,F'=2.

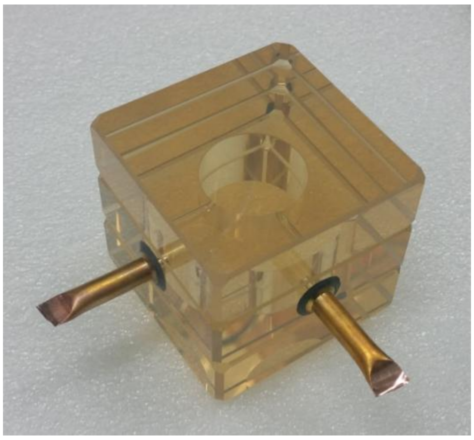

Fig. 1: High vacuum chamber based on Zerodur.

We use tilted 2D MOT configuration [4] to produce slow atomic beam without using push laser. The characteristic of the atomic beam is analyzed about the most probable velocity and velocity distribution. This atomic beam will be adopted to atom interferometer experiment. [5]

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# Recent Development on a Cryogenic Superconducting Cavity Stabilized Oscillator in China

Wang Nuan-rang[1,2], Li Zhi[2], Zhang Zhen-wei[1], Yang ren-fu[1], Zhao Huan[1], Gao Lian-shan[1],

(1. Science and Technology on Metrology and Calibration Laboratory, Beijing Institute of Radio Metrology & Measurement, Beijing 100854, China;

2 Graduate Schools, Second Academy of China Aerospace, Beijing 100854, China )

**Abstract:** The design of cryogenic superconducting cavity stabilized oscillator is achieved based on theory analysis and computer simulation. It includes the design of superconducting cavity with high quality factor, cryogenic environment, PLL and so on. The quality factor of cavity reaches 2E9 and the temperature is 1.6K and the temperature stability is better than 0.001K in experiment. The experiment result is achieved through system debug and optimization that the stability of 1s reaches 4.6E-15 which is the best in ever reported superconducting cavity stabilized oscillator.

**Key words:** Microwave; Superconducting cavity stabilized oscillator; Microwave cavity; Quality factor

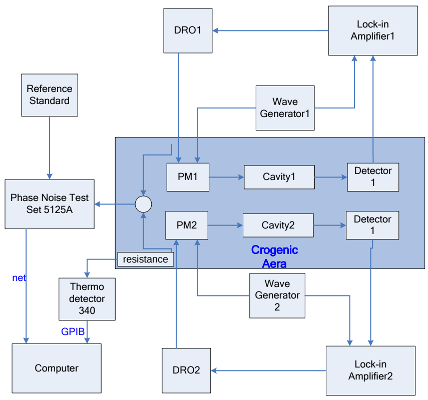


Figure 1 block diagram of microwave frequency source with high stability

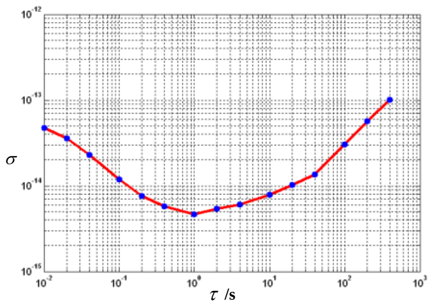


Figure 2 test curve of frequency stability

# Development of an Atomic Interferometer utilizing the Stimulated Raman Transition

Sangkyung Lee, Tae Hyun Kim, Sin Hyuk Yim, Hee Sook Ro, and Kyu Min Shim

Agency for Defense Development, Daejeon, Republic of Korea

Email: sklee82@add.re.kr

We demonstrate an atomic interferometer utilizing the stimulated Raman transition. Figure 1-(a) shows the experimental setup. The magneto-optically trapped and cooled rubidium 87 atoms are freely dropped and the vertically counter-propagating phase-locked Raman lasers [1] are shined on the falling atoms. This type of an interferometer can be used to measure acceleration by gravity. The $\pi/2$–$\pi$–$\pi/2$ Raman pulse sequence realizes the atomic Mach-Zehnder interferometer [2]. To increase performance of the atomic interferometer the optical pumping technique and normalization of the atomic population are adopted. The optical pumping (F = 2 → F' = 2) for 200 μs populates the cold atoms in the magnetic insensitive state (F = 2, mF = 0) which is less sensitive to the spatial or temporal magnetic field variation. The sequence of the three blue-detuned(+1Γ where Γ is the natural line width of rubidium) cooling beam pulses, instead of using the complex optic system such as two thin probe beam line and two fluorescence collection optics [2], enables normalization of the atomic population to decrease the atomic number fluctuation effects on the interference signal. The blue-detuned vertically upward cooling beam is used to probe as well as to blow-out the F = 2 atoms because it accelerates the atoms effectively and maximizes the time-integrated fluorescence. Figure 1-(b) shows the measured interference fringes as a function of linear chirp rate of the Raman detuning. The Raman chirp rate of 25.1 MHz compensates the gravity acceleration. The corresponding measured acceleration of gravity is 9.79 m/s$^2$. Additionally, we also introduce our current progresses on development of an atomic interferometer for rotation measurement.

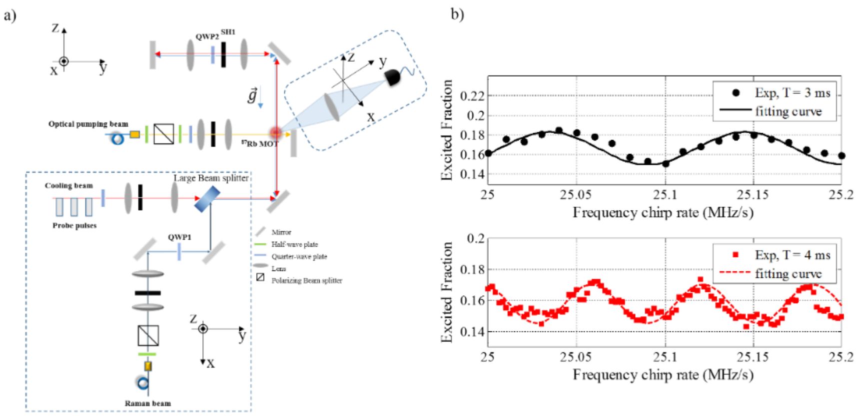


Fig. 1: (a) Experimental Setup (b) Interference fringes as a function of linear chirp rates of Raman detuning.

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# The method on determining invisible satellite-ground clock difference with Inter-satellite-link

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[2] Key Laboratory for Precision Navigation and Timing Technology, Chinese Academy of Sciences, Xi'an/China

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MEO cycle is a half star day. MEO exists two invisible arcs for a station. When the satellite elevation is 10°, visible arcs last about 7 hours, invisible arcs last about 17 hours, satellite-ground clock difference of visible arc is obtained by the way of satellite-ground radio. However, satellite-ground clock difference of invisible arc is obtained by predicting. Satellite-ground clock difference is limited to the prediction precision. Inter-satellite link is a new operation mode, operating on a few stations or no station. Due to the limitation of station layout, this paper proposes determining satellite-ground clock difference of invisible arc by way of inter-satellite link, using target satellite connecting station with relay satellite. Satellite-ground link are composed of target satellite and station. Inter-satellite link are composed of target satellite and relay satellite. It analyzes range of relay-satellite angle. In fact, there exist more relay-satellites. In order to use all the relay-satellites, clock difference of invisible arc is determined with weight. The weight criterion: the inverse square of STD of relative clock difference. The result shows: time-synchronization precision of satellite-ground is less than 0.3ns, std is less than 0.3ns.

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# Using known ground station clock offsets to improve tropospheric delay estimates at NIMT timing station

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GPS satellite clocks are used as time references for time comparison with receiver clock by a direct measurement of signals from visible satellites. The timing receiver is in a fixed location by applying the Precise Point Positioning algorithm using the Position and Navigation Data Analyst (PANDA) software. When the clock offsets are estimated, the correlations between station height and troposphere are existed. This paper shows the estimated tropospheric delay is averagely at 2.5 meters. The repeatability of the station position is at 1 cm vertically.

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# Characterization of the frequency transfer over 300 km of aerial suspended fiber

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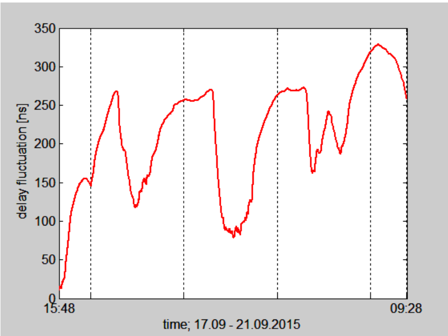
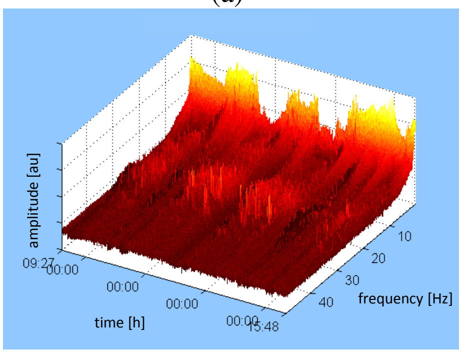
Optical fibers allow obtaining very good stability parameters when used to transfer frequency and time signals over large distances. Among the factors that limit the ultimate performance of the transfer system the noise introduced by an optical fiber is a key one. Published results of evaluation of various in-the-field installations were usually performed with underground [1] or submarine [2] fibers. Such fibers are well isolated from any rapid changes of temperature and from other environmental factors. However, when migrating from various experimental setups to more service-oriented time/frequency distribution links the knowledge about the behavior of delay fluctuations in an alternative optical fiber media, like suspended aerial fibers, is valuable to help predicting the stability of the transfer systems.

In this paper we are reporting on the experiments with a 300 km long suspended fiber running inside the safety wire of the power grid and carrying the 10 MHz frequency signal. In our measurement setup the fluctuations of the propagation delay were sensed by a precision phase comparator (Quartzlock A7MX), sampled 100 times per second and recorded using picoseconds-precision time interval counter (PikTime T4100U). From the measurements (see Fig. 1a for a representative record) we determined the diurnal delay fluctuations (around 150-200 ns), maximum slope of the delay change (±2 ns/min, +50/-80 ns/h) as well as the dynamics of the fluctuation changes within the day (see Fig. 1b). Finally, the data were used to predict the performance of the closed-loop system with an electronic delay compensation [3].




(a)




(b)

Fig. 1: Delay fluctuations registered over three days in 300 km long aerial fiber (a) and short-term spectra showing dynamics of the fluctuations (b).

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# Real-time performance monitoring of fiber optic long-distance time and RF frequency transfer links

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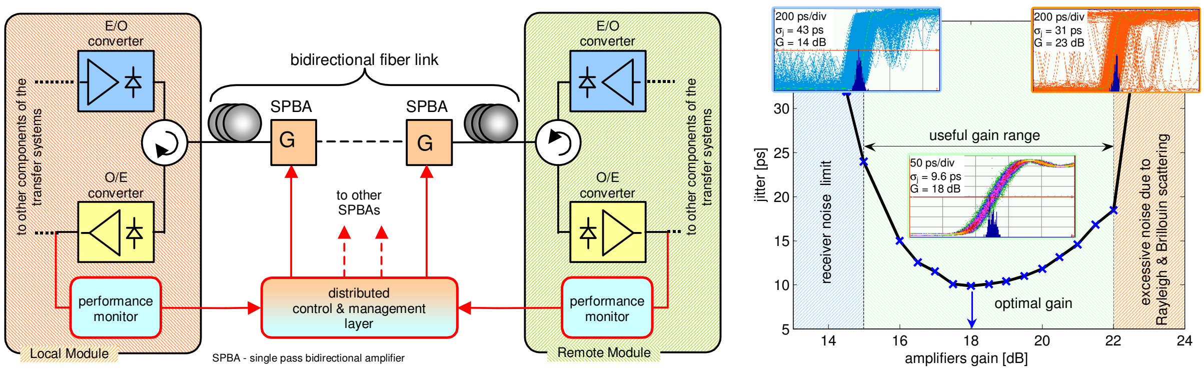
Long-distance fiber optic time and RF frequency distribution links require using optical amplifiers to compensate the loss of the optical fibers. The best performance concerning the stability of transmitted signals is assured in fully symmetric approach that calls for a dark fiber and bi-directional amplification scheme. In such a link the gains of the optical amplifiers must be judiciously chosen to minimize undesirable effects resulting from backscattered signals and other sources of noise, like e.g. amplified spontaneous emission of optical amplifiers, laser phase noise into intensity noise conversion via fiber chromatic dispersion, etc [1]. All these phenomena result in a non-additive broadband noise (extending to a few GHz) that converts into a jitter degrading the performance of the system. Excessive noise may also cause total system malfunction by triggering false signal pulses. In principle the optimal gains of the amplifiers, that minimizes unwanted effects, may be deduced using the model of the link [1]. This approach, however, requires substantial amount of data that are very difficult to obtain.

In this paper we propose the new idea based on monitoring of the performance of bidirectional fiber link in a real time (see Fig. 1a). The key element for this is a circuit for measuring




(a) (b)

Fig. 1: General setup of the bidirectional transfer system with a real-time performance monitoring (a); results obtained with developed jitter monitor in a link composed of 3x100 km fiber spans and two SPBAs (b). Insets show optimum jitter (middle) and excessive noise conditions (upper left and right)

the jitter of RF the signal. The operation and parameters of developed circuit that is able to measure accurately the jitter in the full bandwidth of interest will be presented (Fig. 1b). Using proposed idea and developed circuits it will be possible to realize the distributed control system to trim the gains of SPBAs automatically to into the optimum operation, even when the parameters of the fiber path changes (e.g. due to fiber maintenance).

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# Research on the Zoom Technique of GNSS Timing Signal Granularity

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The 1PPS signal is the standard output of GNSS timing receiver. 1PPS means one pulse per second. The pulse is used to synchronize the device to Universal Time Coordinated(UTC) or the GNSS system time, and it is the recovery of GNSS system time or UTC in the local timing receiver. In a typical design, 1PPS signal is locked with the signal recovery of GNSS 1PPS. The principle of the pulse generating based on the numeric controlled oscillator(NCO) is shown as below.

As shown in the figure 1, 1PPS signal and the 10MHz standard frequency is generated by the local NCO is divided frequency. The counter is used to measure the time difference of NCO 1PPS signal and GNSS 1PPS recovery signal. The microprocessor receivers the time difference data, and generates the NCO frequency control word and the NCO phase control word. According to the NCO frequency control word or the NCO phase control word, the output of NCO is tuned. The real-time 1PPS frequency and phase calibration is realized, and its errors is reduced with respect to GNSS system time.

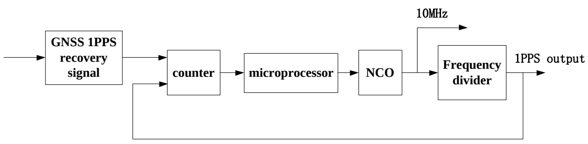


Fig. 1 The principle diagram of GNSS 1PPS generating

More typically, this type of calibration is only applied to the 1 PPS signal phase while the frequency error is left uncorrected. 1PPS signal of GNSS timing receiver is often phase calibrated in discrete steps with anuncorrected frequency error present. If such a calibration was used in GNSS timing receiver, we would observe the 1PPS signal phase error progressing at the uncorrected frequency error. When the phase error grew to the phase step size, a calibration is done and we would observe a phase step in the 1PPS signal phase. This phase step is GNSS Timing signal granularity. This phenomenon is called the sawtooth behavior of the GNSS 1PPS signal.

It assumed that the receiver clock's frequency is f Hz, and the cycle is 1/f s. From the principle to be seen, the 1PPS signal granularity is 1/f s. The amplitude of sawtooth is $\pm 1/2f$ s. Typically, the receiver clock's frequency is less than 100 MHz. For example, the clock frequency of Motorola M12+ is 16.367 MHz, ONCORE is 9.54MHz, and SiRF is 38.192MHz. 1PPS signal of Motorola, ONCORE and SiRF timing receiver often generate the sawtooth behavior, and the amplitude of sawtooth is $\pm$30ns, $\pm$52ns and $\pm$13ns respectively. The sawtooth error is Gaussian, a long term average of the pulse output is not biased by the sawtooth error. But it will have effect on the instantaneous and short-term timing accuracy.

Figure 2 is a small section of the data showing the sawtooth behavior of the raw ONCORE timing receiver's 1PPS signal. The raw 1PPS shows the expected noise dominated by the quantization of the samples at twice the clock frequency of 9.54MHz.

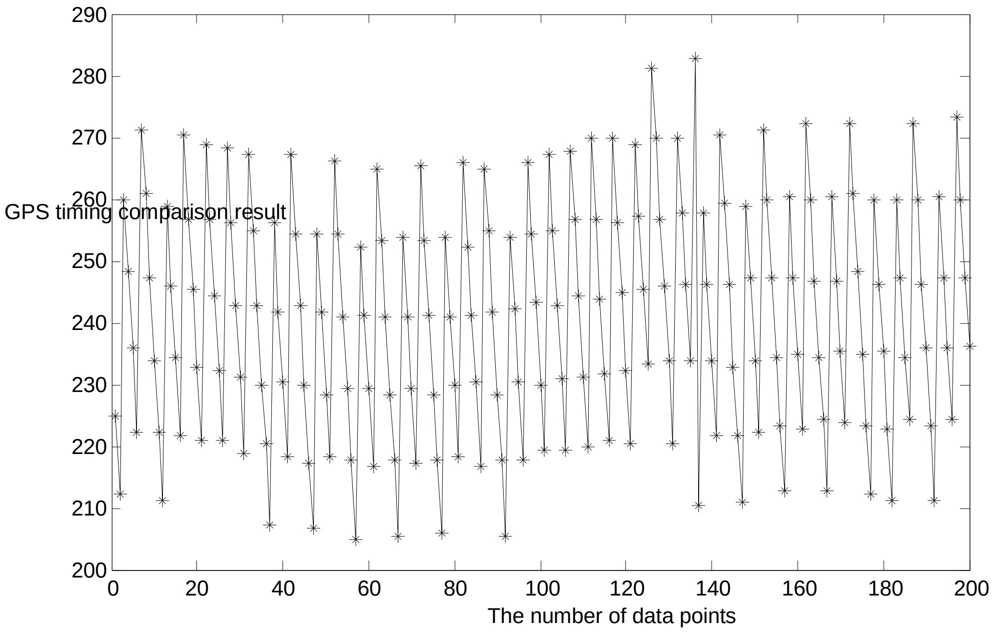


Fig. 2 The sawtooth behavior of GNSS 1PPS

In order to correct the sawtooth error of 1PPS signal, we study the zoom technique of GNSS timing signal granularity, and propose an improved scheme. The programmable delay line technology is introduced in the improved scheme. The granularity of the programmable delay line device can reach 0.25ns. We propose a control algorithm which can realize the zoom of GNSS 1PPS's granularity by the combined with the programmable delay line device. This scheme allows for real-time correction of the quantization error and reduces the residual noise to about 1~2 nanoseconds peak to peak (pk-pk), and improves the instantaneous and short-term timing accuracy of GNSS 1PPS.References.

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# A 1 MHz to 50 GHz Direct Down-Conversion Phase Noise Analyzer with Cross Correlation

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Traditional phase noise analyzers use an analog PLL to recover the phase difference between a local oscillator and the device under test (DUT). Phase locking and compensating the frequency response of the PLL can be cumbersome. Digital phase noise measurements overcome these issues by sampling the RF waveforms directly and calculating the phase difference in the digital domain [1]. This principle can be extended to the microwave domain using additional mixers for the reference and the DUT signal [2].

The new alternative approach requires only down-conversion of the DUT signal. An analog I/Q mixer with an extremely low-noise internal reference source shifts the signal to a low or zero IF, depending on the offset frequencies to be measured. A second receive path enables cross correlation with two narrow-band coupled reference oscillators. This increases the sensitivity by up to 25 dB depending on the number of correlations used.

The complex baseband signals of each path are sampled and the subsequent digital signal processing is done in real time on an FPGA. A digital FM demodulator replaces the PLL as a phase detector and for frequency tracking. The combination of an analog I/Q mixer and a digital equalizer keeps the AM rejection above 40 dB compared to 15-30 dB of a traditional analog PLL. This reduces the chance of a cross-spectrum collapse [3]. An AM demodulator operates in parallel to the FM demodulator which allows for concurrent measurement of amplitude and phase noise. The demodulated signals are filtered, decimated and transferred to the instrument's PC for the FFT and cross correlation processing. The resulting frequency noise spectrum is converted back to an actual phase noise spectrum and displayed as shown in Fig. 1. Phase noise as low as -183 dBc/Hz at 100 MHz carrier frequency and 10 kHz offset can be measured within two minutes.

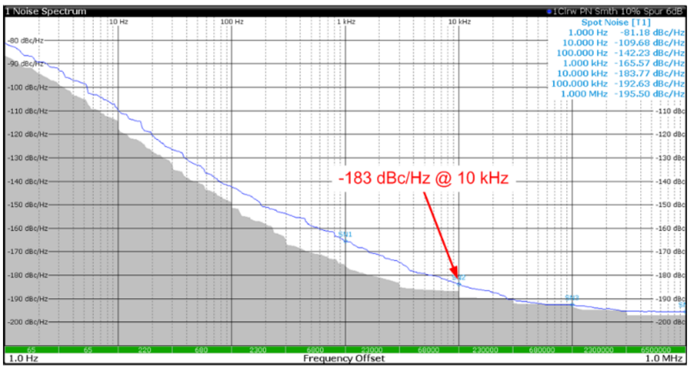


Fig. 1: Two minutes phase noise measurement of a Wenzel 100 MHz-SC Golden Citrine Crystal Oscillator with 19 dBm output level

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# Fiber-optic time distribution with the autonomous calibration of dispersion-induced offset

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To obtain high stability of the time transfer and to make possible autonomous calibration of time offset (delay) of an output 1 PPS signal, a bidirectional transmission in single fiber is commonly used. However, even in this situation the forward and backward propagation is not strictly symmetrical, which affects calibration considerably [1]. One of the main reasons of this asymmetry is the chromatic dispersion occurring in optical fibers, causing that speed of the light is slightly different for forward and backward signals, which are transmitted with deliberately detuned wavelengths.

In our time and frequency distribution technology - ELSTAB - the calibration of the output timescale offset is performed by measuring the round-trip delay of the 1 PPS signal, dividing this value by two, and applying necessary corrections, which are: constant asymmetry of propagation delays in our hardware, correction for Sagnac effect, and asymmetry caused by the dispersion of particular fiber path. As we demonstrated in our previous works, the term related to chromatic dispersion has dominant contribution to calibration uncertainty, especially in long-haul links [2].

In this presentation we will describe a new and precise method of determining the dispersion-caused offset (correction). After deactivation of a delay locked loop (normally stabilizing propagation delay in our system) we apply small wavelength excursions of the laser in the local module, and measure resulting changes of the round-trip delay with precise TIC or digital oscilloscope - see Fig. 1. After necessary data processing this procedure gives us accurate value of the correcting factor related to the chromatic dispersion.

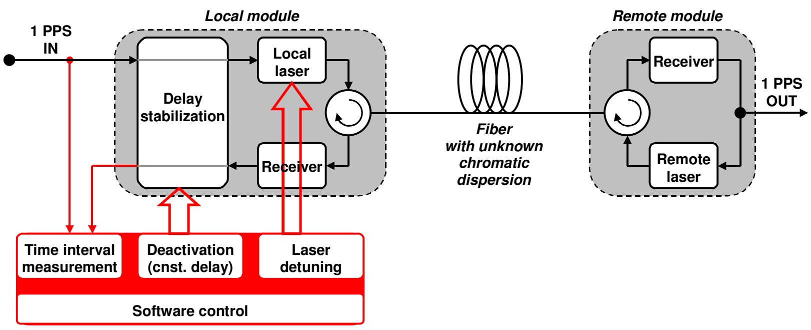


Fig. 1: Schematic illustration of the dispersion measurement.

Practical evaluation of the proposed method will be presented for various fiber types and lengths. Obtained results will be compared with dispersion estimation based on the fiber vendor's data, and measured with standard dispersion measurement devices used in optical telecommunication. As will be proved, application of this new method allows obtaining absolute calibration of the timescale delay with uncertainty less than 20 ps.

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# Advances in RF SAW Devices: What are Demanded?

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A large number of surface acoustic wave (SAW) filters are embedded in a current smart phone, and their annual production is several tens of billions. Since total performances of current mobile communications are often limited by those of SAW devices, drastic enhancement of their performances is still strongly demanded in addition to further reduction of physical size and price.

This talk reviews current status and future prospect of radio frequency (RF) SAW devices used in mobile communications. Then a survey is given to demands necessary for realization of near future communication systemss.

Residual Losses Although current SAW devices exhibit extremely high performances, there still remain unknown excess losses. One possible mechanism is energy leakage to surroundings. We investigate how such leakage occurs using the full wave analysis and a behavior model, and try to find effective countermeasure(s) to overcome the problem. The laser probe system was developed to visualize the device resonance pattern, and is used for detailed investigation. We will show how the system is effective for the purpose.

Temperature Stability Most of all materials become soft with the temperature $T$. Then the filter passband shifts downward with $T$. Its cancellation called the temperature compensation (TC) is realized by the use of $SiO_2$, which becomes stiff with $T$. Since $SiO_2$ is not piezoelectric, thinner $SiO_2$ is better. It is known that $SiO_2$ properties including the temperature coefficient of elasticity (TCE) change drastically with the material preparation. We proposed to use the FTIR as a guideline to search “excellent” $SiO_2$ films for SAW devices.

The wafer bonding is another technique for TC. After a piezoelectric wafer such as $LiNbO_3$ and $LiTaO_3$, is bonded with a stiff substrate like sapphire, the piezoelectric wafer is thinned by polishing. Due to stress caused by the bimorph effect, TCE is improved. In contrast to the $SiO_2$ deposition, the wafer bonding scarcely influences to the other performances.

Nonlinear Signals Introduction of new communication schema always makes requirements given to RF SAW devices tougher and tougher. One example is the linearity. Although SAW devices are quite linear, further reduction of nonlinearity is demanded. There are two questions: “(1) where and how does the nonlinearity occur?” and “(2) how do we measure extremely weak signals?” We developed a behavior model for this case and compared with the experiment. We will show how well the nonlinearity behavior is understood until now.

Power Durability Duplexers for pico-cell baseband stations may expand applicability of SAW devices. For such application, not only the linearity but also the power durability are critical. Again, there are two questions: “(1) where and how does the failure occur after exposure to high RF power?” and “(2) how do we measure the mean time to failure of these devices?” We investigate the latter issue in collaboration of SAW industries all over the world so as to establish an international standard as the IEC activity.

New materials Achievable performances of these devices are inherently limited by the choice of the piezoelectric material. From this aspect, we pay much attention on paraelectric Sc doped AlN films offering anomalously strong piezoelectricity and low acoustic and dielectric losses in the GHz range. ScAlN films can be deposited to a large area by reactive sputtering. Thus ScAlN seems for applicable to wideband and low loss SAW devices operating over 3 GHz, which current technologies may not be feasible.

# Coherent Population Trapping Ramsey Resonance in Slow Rubidium Beam.

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Quantum frequency standards have wide applications in such systems of navigation as GLONASS, GPS, GALILEO. For this reason the creation of compact quantum frequency standards having, at the same time, high accuracy remains an important problem in modern quantum electronics. One of the more promising ways to solve this problem is to use the Coherent Population Trapping (CPT) effect.

The width of CPT resonance can be much less than atomic natural linewidth. Even more narrow resonance can be observed if CPT is registered by Ramsey method [1]. In [2] a scheme of a new mobile slow-beam microwave atomic clock was proposed. This scheme assumes usage of a modified Zeeman slower. Utilization of the CPT resonance with Ramsey registration technique allows one to refuse from the microwave cavity and thus to decrease the size of the clock and its power consumption.

In the paper [3] we analyzed the formation of a CPT-Ramsey signal in this standard for the model case of a single-velocity narrow atomic beam. Various possible schemes of working transitions with linearly polarized radiation were considered. An influence of the main setup parameters such as light intensity, magnetic field intensity and thickness of laser beams on the amplitude and width of the resonance was studied.

In the present work, we study the influence of the finite width of atomic beam, its angular divergence and residual beam velocity spread on the parameter of CPT-Ramsey resonance for the scheme proposed in [2]. We calculate the time dynamic of atomic internal state in the beam of rubidium 87 interacting with two spatially separated region of bichromatic field. The calculation is based on density matrix approach. According to results obtained in [3] we restrict ourselves by the case when two components of bichromatic field are orthogonally linearly polarized and tuned at transition to the $F_e = 2$ level of the D1 line. All Zeeman sublevels of this and the ground states are taken into consideration. For this geometry we analyze the dependence of figure of merit of the CPT-Ramsey resonance on the observing conditions.

This work was supported by the Ministry of Education and Science of the Russian Federation (State Order No. 3.1446. 2014/K).

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# Stability and Durability of Resonant SAW Strain Sensors

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SAW strain sensors have been developed and manufactured in low volumes for a number of applications, in particular for passive wireless sensing of torque, force, strain in automotive and power generation industries. Acceptance of wireless SAW strain sensors for high volume applications depends on their proven stability and durability. A lot of research was done on this subject in the 70-80s with regard to SAW devices as frequency stabilizing elements in oscillators [1, 2]. However, there were no stability and durability data published for SAW strain sensors. The aim of this paper is to report some results of fatigue and accelerated aging tests for packaged and unpackaged resonant SAW strain sensors working at 428-437 MHz.

Resonant SAW strain sensors are subject to the same factors influencing their stability as the SAW resonators in oscillators: stress relaxation in the substrate and the Al film, Al film oxidation and adsorption/desorption of water molecules and other contaminants, etc. However, there is an extra factor that is specific to strain sensors, namely the state of the interface between the sensor's substrate and the part where the strain is measured. Very often this interface is formed by a thin layer of a stiff adhesive that can have a residual stress after curing. This stress relaxes with time causing the frequency shift. Besides, mechanical properties of the bond layer can change with time causing variation of the strain sensitivity. Finally, the bond layer can experience fatigue causing gradual or sudden delamination of the SAW substrate and failure of the sensor. The SAW substrate itself, being made of a brittle material, can also crack under a high strain.

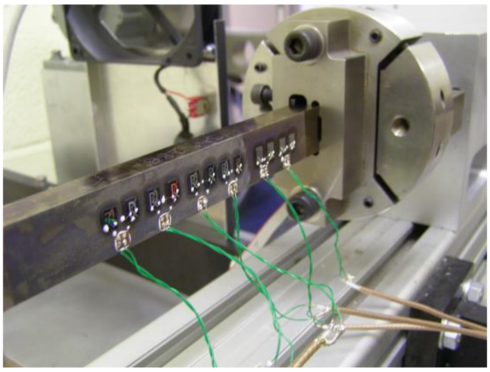

Fig. 1: Fatigue test rig for bonded SAW strain sensors.

Fatigue testing of the bonded unpackaged SAW sensing elements was performed by applying up to 18 million cycles of shear strain with the amplitude of ±453με in a specially designed rig (Fig. 1). The tests showed no degradation of the strain sensitivity of the resonant frequency for the samples bonded with a cyanate ester adhesive at least up to 13 million cycles. There were no bond failures and SAW substrate cracks during the whole test. The fatigue test has shown that the bond between the SAW device and the metal part is quite reliable provided the right adhesive is used. Accelerated aging test was also performed for the SAW strain sensing elements bonded to the bottom of metal packages and sealed in the inert gas atmosphere. Aging was performed for 1800 hours at 125°C for the packaged sensors both unbounded and bonded to a steel bar. The maximum difference frequency drift of the sensors was 3.05 kHz corresponding to a sensor zero drift ≈0.14…0.62%FS per year at 90°C.

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# Back ground noise suppression in CPT based atomic clock by differential detection

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The conventional CPT atomic clock, which uses VCSEL driven by the microwave modulated current to provide linearly polarized multichromatic laser to interact with atoms in which two frequency components generating CPT resonance with atoms, detects the transmission beam with photo detector and extracts CPT signal from the detector output [1]. Although the scheme is suitable for miniature clock implementation, the frequency stability of the clock is relatively low. In the detector output, excepting the two components, the other components (unwanted components) only contribute background noise, and the strong background noise is an important source deteriorating the frequency stability.

We present a scheme with which the VCSEL outputted linearly polarized mutichromatic laser beam directly interacts with atoms in magnetic field, a polarizing beam splitter separates the transmission beam into two linearly polarized ones which are separately detected with two photo detectors, and a differential signal output is obtained by subtracting the two detector outputs. As the polarization directions of the two components interacting with atoms change due to Faraday effect while that of the unwanted components do not change, in principle in the obtained differential signal the noise background from unwanted components can be eliminated and the remains is only from the two components.

The contrast, defined as CPT signal intensity divided by the background noise intensity, of the conventional CPT atomic clock is at 5% level, while our experimental study result reveals that the background noise of differential CPT signal can basically be eliminated with this scheme. The other benefits of the scheme include increasing the availability of atoms, realizing narrower line width CPT signal, suppressing the frequency-amplitude conversion noise, etc. We evaluate according to the experimentally recorded CPT spectral line and conclude that the frequency stability can be improved by two orders of magnitudes compared with the conventional scheme, at the same time the size and power consumption of the CPT atomic clock can be kept at the same level [2].

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# Finite Size Effect on Scale Factor for an Atom Ball Gyroscope

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Laser pulse driven atom interferometers [1] have demonstrated their ability to realize absolute measurements with state-of-the-art accuracy and sensitivity compared to other technologies. So far these results have required laboratory-size experiments, but current efforts are underway to develop more compact setups for in-field inertial navigation and geodesy.

An atom interferometer scheme that allows a simultaneous measurement of 2-axis rotations and 1-axis acceleration in an effective 1 $cm^3$ volume will be presented. Usually counter-propagating atomic sources are required to decouple phase shifts induced by rotation and acceleration [2] which leads to a larger and more complex apparatus. To accomplish this decoupling with a single atomic source, we extend the Point Source Interferometry technique realized initially in a 10-meter tower [3] to the compact regime.

We have obtained spatially resolved interference fringes in the atomic cloud (Fig. 1) for short free-fall durations. In this compact regime, the atom cloud can no longer be treated as a point source, introducing a bias in the scale factor from the simple point-source limit. As this bias depends on the initial phase-space density, we explored the scale factor deviation with different initial cloud sizes and observed the transition from the point-source to finite-size situations.

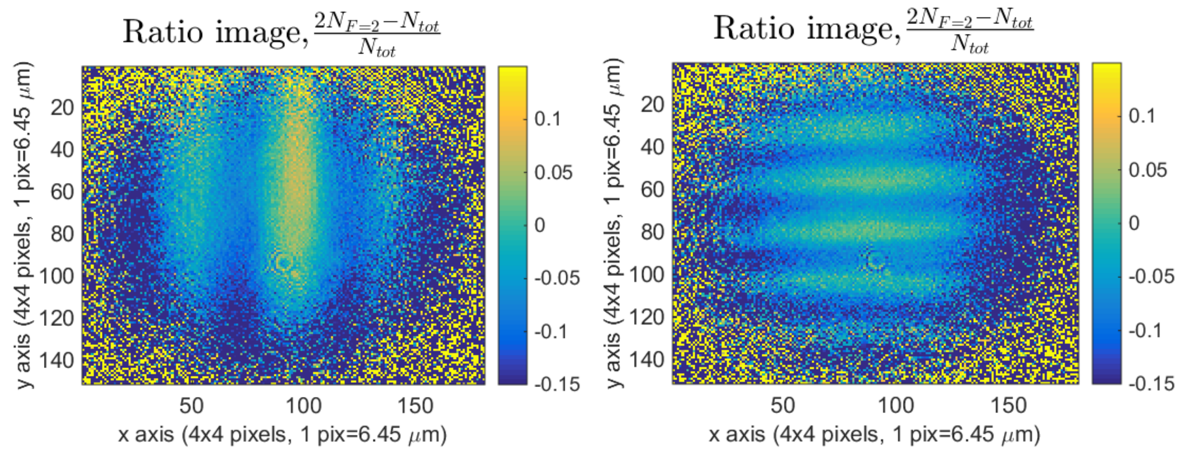


Fig. 1: Spatially resolved interference fringes for a total interaction time 2T=16 ms induced by a rotation of Ω=74.3 mrad/s along y (left) and Ω=135.8 mrad/s along x (right). Rotations are simulated by rotating the retroreflecting mirror of one of the Raman beams during the interferometric sequence.

As a mid-term objective, we intend to push toward the limits of this interferometer. We expect the upper limit of the rotation dynamic range to be determined by the atomic cloud's initial size and the lower limit to be set by atomic shot noise. With a better SNR, we should be able to measure the Earth's rotation to characterize the gyroscope stability. Ultimately, we hope to develop a compact inertial sensor that would complement other sensing technologies.

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# Towards redefining the SI in 2018

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During its 25th session held in November 2014 in Versailles, The General Conference on Weights and Measures (CGPM) re-confirmed its intention to adopt new definition for the following base units: the kilogram, the ampere, the kelvin and the mole, leaving the present definition of the second, meter and candela unchanged. The new definition of the units should be based on fixed numerical values of fundamental constants respectively: the Planck constant h, the elementary charge e, the Boltzmann constant k and the Avogadro constant NA. The new definitions are chosen to maintain continuity, so that the magnitude of the four redefined units in the "new SI" will be essentially identical to their magnitude at the moment of adoption.
The limits of the present system will be presented first, then the choice that have been made to arrive at these proposals, and further details of the change involved in the "new SI".

# The NAC – A Miniature CPT Rubidium Clock

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Here, we report of the design and characterization of a miniaturized Rubidium Frequency Standard named NAC1 (Nano Atomic Clock 1), now commercially available (see fig. 1). Recently, the introduction of the effect of coherent population trapping (CPT) has led to a substantial reduction in power and size of commercial atomic frequency standards. The CPT effect renders a narrow transparency window in the transmission spectrum of an atomic vapor cell, which can be used as the clock signal of an atomic standard. Here, utilizing this effect in a traditional glass technology, we are able to introduce a compact, and low power frequency standard.

The basic principal of operation is hereby briefly described. First, an FPLL is used to lock a 10MHz TCXO to a 3.4GHz VCO. Next, the VCO modulates the light source (a VCSEL) current (at the D1 line of Rb) thereby producing two coherent sidebands to excite a Λ-type system for the CPT. When the two sidebands separation equals the Rubidium "clock frequency" (at ~6.8GHz), a narrow transparency window emerges. The transparency peak is used to lock the TCXO to the clock transition.

NAC1 uses 5 interrelated loops for controlling the laser wavelength, the RF power, the cell and laser temperatures and of course the clock frequency. We eliminate the use of temperature sensors, by inferring the temperature directly from the atomic vapour density. The interlaced loops operate in a time division multiplexing scheme with three states allocated for each loop thus achieving a noise reduction. An additional control loop allows disciplining the clock to an external 1PPS (e.g., arriving from GPS).

Fig. 1: Photograph of NAC1 with the dimensions of $41x35x22mm^3$, power consumption of 1.2W, demonstrating a frequency stability (ADEV) of $8\cdot 10^{-12}$ at 1000s, and an aging of $3\cdot 10^{-10}$ per month.

The Rubidium vapour cell is a miniature glass ball with transparent resistive coating which allows for direct heating. With this geometry the magnetic field induced by the heating current is minimized close to zero. The use of the traditional glass cell technology which has been proven in Rubidium clocks for years ensures high reliability and minimizes risks. For the similar reason we use Rubidium rather than Cesium due to the long Rubidium heritage in vapour cell atomic clocks. In addition the paper discusses the light shift effect (AC Stark shift) and its translation to RF power shift as well as means to overcome this shift.

The atomic standard outputs 10MHz and 1PPS, has dimensions of $41x35x22mm^3$ and its power consumption is 1.2W. When free-runs it demonstrates a frequency stability (ADEV) of $8\cdot 10^{-12}$ at 1000s averaging time, and an aging (drift) of $3\cdot 10^{-10}$ per month. We are working on a next generation which will reduce the power consumption to 600mW.

# An Ultra Stable Oscillator for the 3GM Experiment of the JUICE Mission

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An Ultra Stable Oscillator (USO) is being developed by AccuBeat for the 3GM radio occultation experiment of the ESA JUICE mission. The USO will provide a highly stable reference signal for the one way (space to ground) radio link in X and Ka band to investigate the structure of the neutral atmospheres and ionospheres of Jupiter and its moons. 3GM stands for "Gravity and Geophysics of Jupiter and the Galilean Moons" and also aims to use radio tracking from ground to map the gravity fields of Jupiter's icy moons, and to reveal internal oceans on two of them.

Fig. 1: The USO, an Ultra-Stable-Oscillator, $15x13x10cm^3$, based on quartz resonator

The USO is a compact $15x13x10cm^3$ oscillator, based on a quartz crystal resonator, exhibiting short term stability of parts of $10^{-13}$ for averaging times of 1s to 1000s. This paper briefly reviews the oscillator design and the critical issues to be tackled. We analyze the design using the quartz resonator key parameters and measure its internal noise. We use the Leeson model which provides the transfer function of the sustaining amplifier noise to the oscillator output noise. A key issue is the temperature stabilization of the crystal resonator and its sustaining electronics. We use a double oven design to achieve a very high temperature stability at the relevant time constants of 1 to 1000s. Key environmental space requirements to address are operation under thermal vacuum, irradiation at the level of 50krad, and hardened structure to withstand vibrations and shock during launch. Analysis and simulations were performed to verify meeting these requirements. The variation of the Jupiter magnetic field during a radio occultation was evaluated and its effects on the oscillator stability have been assessed.

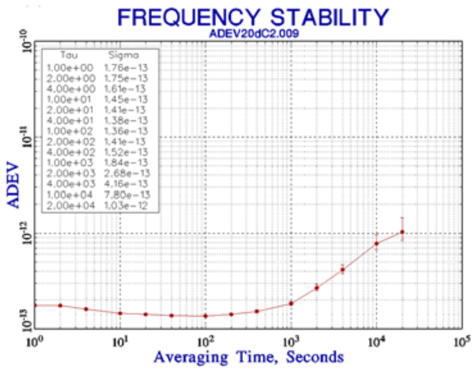


Fig. 2: Measured instability (Allan Deviation) on a partial engineering model

A partial engineering model of the USO (PEM) was built and tested in thermal vacuum. The full EM will be completed in March 2018 with the addition of the internal power supply. The PEM has demonstrated a frequency stability below 2E-13 for a 5MHz output, at an averaging time 1s to 1000s (see fig. 2), thus meeting the requirements for technology readiness level 5 (TRL 5), according to the ECSS standards.

**Acknowledgements:**

This work is sponsored by the Israeli Space Agency. We thanks Yohai Kaspi from the Weitzman Institute, Luciano Iess from the Sapienza University of Rome for their support, and Enrico Rubiola from FEMTO-ST Institute, Besancon for advice and for the characterization of resonators noise.

# Absolute frequency of the inter-combination line in $^{171}$Yb with use of the clock transition

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We report on the absolute frequency measurement of the 6s$^2$ $^1S_0$ (F=1/2) - 6s6p $^3P_1$ (F=3/2) transition in $^{171}$Yb. Knowledge of this frequency will aid those searching for the $^1S_0$ (F=1/2) - $^3P_0$ (F=1/2) clock transition without access to highly accurate frequency standards. Interest in the $^1S_0$ - $^3P_0$ transition in the fermionic Yb isotopes is attracting significant attention; e.g. for studies in quantum many body physics [1] and quantum computation [2], along with clock applications [3].

We use saturated absorption spectroscopy (SAS) on a thermal Yb beam, where fluorescence is detected with a photomultiplier cell and frequency modulation is applied to the light allowing for third harmonic detection with a lock-in amplifier. The SAS produces a dispersive signal to which a 556nm laser is stabilized. Helmholtz coils in close vicinity of the SAS zone are used to null the magnetic field in the vertical direction (Fig. 1). Sub-harmonic light at 1112nm has its frequency measured by use of a frequency comb that is referenced to a hydrogen maser. We have validated our measurements by performing clock transition spectroscopy on $^{171}$Yb atoms held in a magneto-optical trap (MOT), and finding agreement with previously reported values to within 10kHz. The 578nm probe light for the clock transition was stabilized by locking its sub-harmonic at 1157nm to a 400(20)×10$^3$ finesse optical cavity. The MOT light and 578nm light are switched interchangeably at 1.25kHz producing a ‘steady-state’ cloud of atoms in a light-shift free probe scheme. The clock line is detected through ground state depletion as the 578nm light shelves atoms to the $^3P_0$ metastable state.

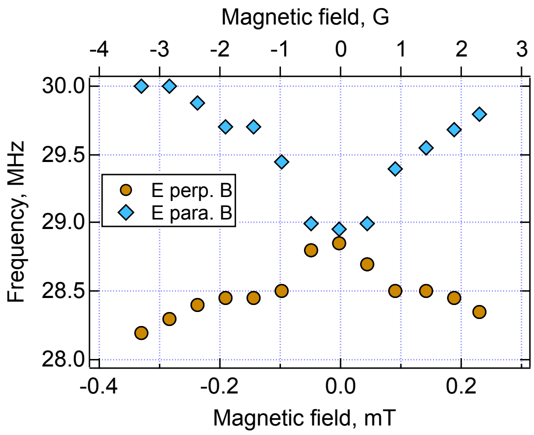


Fig. 1: $^{171}$Yb $^1S_0$ - $^3P_1$ (F=3/2) frequency (offset from carrier) versus magnetic field strength for two **E-B** configurations. The point of equal frequency coincides with other determinations of zero B-field.

Frequency measurements of both the inter-combination line and the clock line were made almost daily over the course of a month as a test of the reproducibility. The statistical uncertainty of the $^1S_0$ - $^3P_1$ [$\sigma/\sqrt{(N-1)}$] frequency measurements is below 20kHz. For the systematic uncertainty we include Zeeman effects, wavefront curvature, and frequency counting errors. The mean frequency is 539 390 405 430 (190) (16) kHz [3]. An absolute frequency for the same line can be inferred from a result in Pandey et al [4]. We find our frequency to be higher by 39.4MHz. We have compared line characteristics between the $^{171}$Yb (F=1/2-3/2) and $^{171}$Yb (F=1/2-1/2) lines, and find similar behaviour including a sharp saturated absorption peak (rather than dip) at ±3.5G (±0.35mT). We are still seeking an explanation for this effect, which is not observed for any of the other isotopes.

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# TWSTFT Results by using Software-Defined Receiver Data

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The new development of two-way satellite time and frequency transfer (TWSTFT) focuses on enhancing its short-term stabilities, e.g., employing dual pseudo-random noise (DPN) codes, and carrier-phase (CP) based TWSTFT [1, 2]. However, the accuracy of TWSTFT is still limited due to instabilities of signal arrival time. Traditional TWSTFT often suffers the problem of diurnals. The sources of diurnals may be not only the variation of physical propagation delay, but also a composition involving signal interferences and imperfection of TWSTFT receivers. A software-defined receiver (SDR) was originally designed for implementing the DPN-based or CP-based TWSTFT. We further used it to accurately measure the arrival time of code signal transmitted by SATRE modem, and then we found it exhibits the capacity against the TWSTFT diurnal variations [3].

There is no change for the current TWSTFT system except a power splitter is added to divide reception signal to the SDR. Then, two parallel TWSTFT (i.e., using SATRE modem and SDR) can be performed simultaneously. The SDR systems have been successfully installed at TL, NICT and KRISS since 2015.

Figure 1 shows hourly TWSTFT data for the KRISS-TL link by using SDR and SATRE modem. The upper plot shows time difference data from MJD 57325 (30 October 2015) to MJD 57336. The diurnal variations are clear for SATRE data, but unobvious for the SDR data. The bottom plot shows their time deviations (TDEV). The TDEV at 1 hour are 31 ps and 93 ps for SDR and SATRE data, respectively. The TDEV plot of SATRE modem shows a peak of 134 ps at 8 hours, where the TDEV of SDR is only 32 ps. The both TDEV curves eventually meet for the averaging times larger than 2 days.

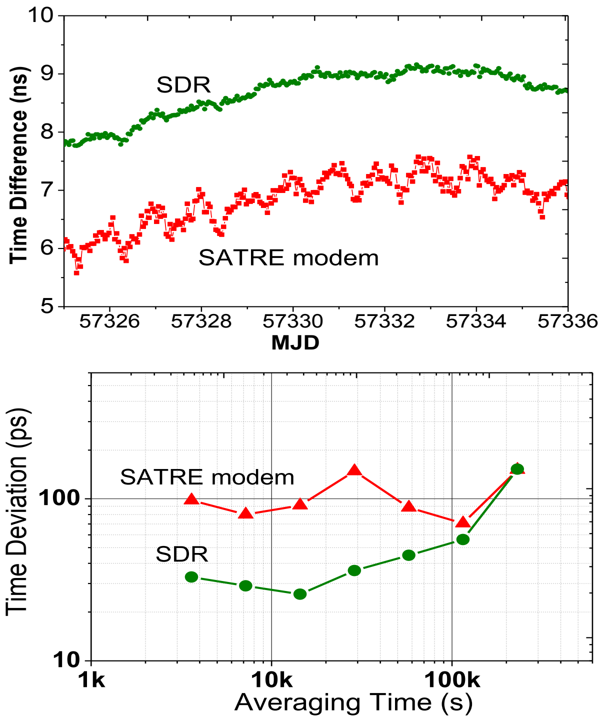


Fig. 1: TWSTFT results for the KRISS-TL link. The upper plot shows time differences shifted for display, and the bottom one shows time deviation for time transfer data by using software-defined receiver and SATRE modem.

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# Comparison of Different Amplification Concepts for Multiple Point Frequency Dissemination

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Within the Collaborative Research Centre SFB 1128 (http://www.geoq.uni-hannover.de) we plan to distribute light with a reference frequency from PTB, Braunschweig, to several institutes in Hannover, i.e. the Albert-Einstein Institute (AEI), the Institute for Quantum Optics of the LUH (IQ-LUH), and the HITec centre which is currently under construction. The goal is to provide an ultra stable and accurate optical frequency near 194 THz at these institutes using the concepts presented in [1, 2] and enable tests of the transportable Sr optical clock [3] developed also within the SFB. We aim for a frequency transfer instability of the link below $1\times10^{-15}$ at 1 s of averaging time and an accuracy below $1\times10^{-18}$.

To reach our target to transfer the optical signal to different sites simultaneously, we extend the fiber link we used previously for frequency dissemination between PTB and IQ-LUH [1] towards the institutes AEI and HITec, see Fig. 1. Using multi-point distribution as presented in [4, 5] it is possible to extract an ultra stable frequency at each site. In contrast to [6], this method requires only one stabilization system and transmits only two frequencies via the link.

Each extraction point, however, introduces additional losses of about 3 dB, which has to be considered in the overall power budget of the link. Since amplification using a single bidirectional erbium-doped fiber amplifier (biEDFA) at the remote end at PTB [1] provides insufficient gain for our task, we will investigate and compare other schemes by using either biEDFAs or fiber Brillouin amplifiers (FBA) at sites at PTB and/or Hannover. Criteria for the comparison are: (1) minimal crosstalk between the amplifiers and the extraction points, (2) sufficient optical power to directly enable local applications (~0.5 mW) without an additional phase locked laser [5], (3) continuous operation of the stabilization system.

To date, we have re-established the 146 km link connecting PTB and IQ-LUH in Hannover, now using an FBA instead of a biEDFA at PTB. The FBA with a typical gain of 42 dB almost compensates the current single pass loss of 44 dB of the link. The relative instability (ModADEV) measured at the remote end (PD 2) is $1\times10^{-16}$ at 1 s of averaging time. As a first test, a transportable, ultra stable cavity will be characterized in Hannover via the fiber link.

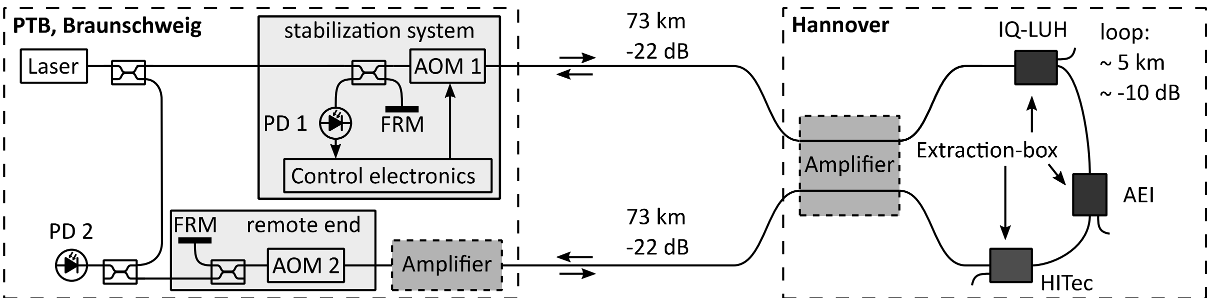


Fig. 1 Overall schematic of multiple point frequency dissemination PTB-Hannover

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# Quantum logic state detection for molecular ions

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High precision spectroscopy of molecular ions is a promising tool for the investigation of fundamental physics, e.g. the search for variation of fundamental constants, an electron electric dipole moment or parity violation in chiral molecules. However, the practical implementation has remained inaccessible due to the lack of efficient state preparation and detection schemes.

Here, we present the first demonstration of a non-destructive rotational state detection for a single molecular ion trapped in a linear Paul trap [1]. For this purpose, we implement a quantum logic operation between the molecular $^{24}MgH^+$ ion and a co-trapped atomic $^{25}Mg^+$ logic ion.

The experimental sequence consists of sympathetic ground state cooling with the logic ion [2] and the implementation of a state dependent optical dipole force (ODF) that transfers the molecule's internal rotational state $J$ to a shared motional qubit ($|\uparrow\rangle_m, |\downarrow\rangle_m$, depicted as Bloch spheres in Fig. 1**b**,**c**). Afterwards, the motional qubit is mapped onto the atomic qubit where it can be detected efficiently by state dependent fluorescence.

A typical signal is shown in Fig. 1**a** and can be interpreted as a blackbody radiation (BBR) induced quantum jump.

Furthermore, the detuning dependence of the signal allows us to determine the resonance frequency of the $A^1\Sigma^+ \rightarrow X^1\Sigma^+$ transition.

In contrast to previously employed destructive state detection techniques, the demonstrated non-destructive detection allows spectroscopic investigations of a single molecular ion with high duty cycle, paving the way for highest precision spectroscopy of molecular transitions

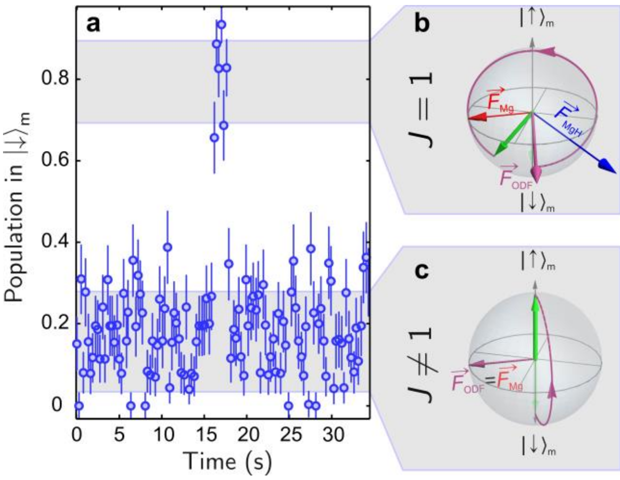


Fig. 1: (**a**) Typical detection event. (**b**) and (**c**) Bloch sphere representation of the motional qubit. Initially the molecule is not in the J=1 state and the motion is only influenced by the ODF on the co-trapped Mg ion (see **c**). After a BBR induced quantum jump into *J=1* an additional force (see **b**) on the molecule leads to population in the $|\downarrow\rangle_m$ state.

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# Study of Ion Beam detection in Cesium Beam Frequency Standard with Feedback Ammeter Circuit*

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The paper describes a new scheme adopting the feedback ammeter circuit to amplify ion signal generated by physical package of cesium beam frequency standard with magnetic state selection. The input of the feedback ammeter circuit is of picoamp level and directly connected with the first dynode of electron multiplier, and the leading out wire of final dynode of electron multiplier should be shielded from environmental interference. The feedback ammeter circuit is classic "Transimpedance Amplifier" or "Current to Voltage" converter circuit [1]. Here the LMC 6062AIN operational amplifier is used for the ultra-low input bias current application. The value of the feedback resistance is 100GΩ. Guard shield is included in the feedback circuit and in the signal input connection for the picoamp current amplification. The feedback circuit is protected with Permalloy metal box. Moreover, a low-pass filter has been designed at the output of amplifier in order to remove alternating current interference.

With the feedback circuit, the cesium ion signal from cesium beam tube with 1.0pA can be amplified to 75mV, as shown in Fig. 1. The noise of the amplification signal is lower than 1μV with 1/4Hz bandwidth [2], thus the signal-to-noise is 97dB, which is over signal-to-noise of cesium ion flux caused by shot noise. According to theoretical relation between standard deviation with signal-to-noise of picoamp level ion flux for cesium beam frequency standard, the Allan standard deviation is approximately 1.1E-11@1s [3].

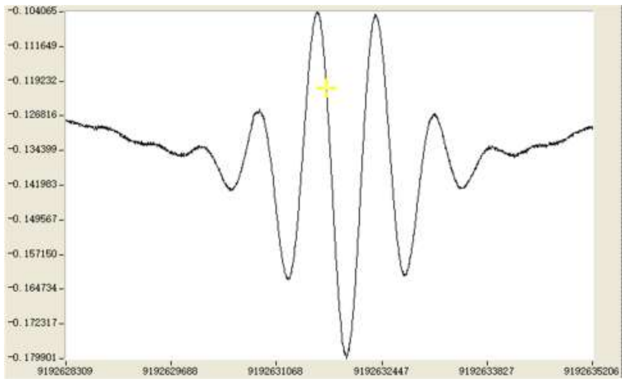


Fig. 1: Ramsey signal of cesium beam tube with feedback ammeter circuit.

The cesium beam tube with feedback circuit is currently locked with frequency standard circuit. The duration of square-wave interrogation is up to 1.6s on each frequency point. It has been achieved that short term stability of 2E-13@10000s compared with a 5071A cesium clock.

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# Magnetic state selection impact on double resonance effect in H-maser

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It is well known double resonance effect in a hydrogen maser appears in a two-photon process in which the Zeeman sublevels of the hydrogen atom ground state hyperfine structure are involved when applying transverse magnetic field near the Zeeman frequency. As a consequence of this process maser power falling due to weakening of the dipole coupling $|F=1,\ m_F=0\rangle \leftrightarrow |F=0,\ m_F=0\rangle$ and maser shift due to amplification of the dipole coupling $|F=1,\ m_F=1\rangle \leftrightarrow |F=0,\ m_F=0\rangle$ and $|F=1,\ m_F=-1\rangle \leftrightarrow |F=0,\ m_F=0\rangle$ occur near the Zeeman frequency. The first analytic calculation of the effect was performed by Andresen using bare atom basis [1], then Humphrey confirmed this calculation by numerically solving dressed basis Bloch equations [2]. But both calculations were realized for perfect magnet ensured state selection $N_{1,1}= N_{1,0}= 1/2$ и $N_{1,-1}= N_{0,0}= 0$ that is not feasible in practice. In this paper new modified Bloch equations intended for arbitrary state selection system have been obtained and calculated. As a result an analysis of state selection performance impact on double resonance in H-maser is produced. In figure 1 the results of the calculation performed in four fundamental different cases of the magnetic state selection are represented.

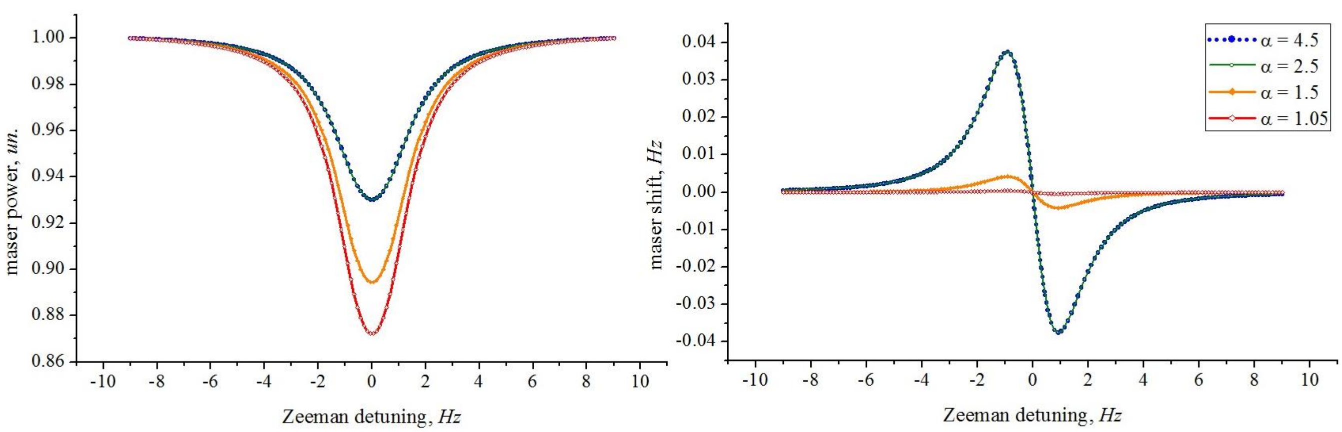


Figure 1. The curves of normalized maser power (*left*) and maser frequency shift (*right*) versus the Zeeman frequency detuning. In the calculation the next parameters $\gamma_1= \gamma_2= \gamma_Z= \gamma+r$, $\gamma= \pi$, $r= 2\pi$, $|X_{12}|= \pi$, $|X_{24}|= 2\pi$, $Q_c= 3.5\cdot10^4$ were used. The case of state selection quality factor *α=4.5 (blue)* corresponds to bad *usual* state selection, *α=2.5 (green)* – perfect *usual* state selection, *α=1.5 (yellow)* – imperfect *single* state selection (70 % of the operating atoms in total atomic flux), *α=1.05 (red)* – perfect *single* state selection (95 % of the operating atoms).

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# The Raman laser system for Mach-Zehnder Atom interferometry

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Abstract: We produced two Raman-laser beams with a frequency offset of 6.834GHz by injection-locking of a master diode-laser to a slave diode-laser. The master laser was phase-modulated at 6.834 GHz with an Electro-Optic Modulator and then injected into the slave laser that was oscillating around one of the side-bands. The relative linewidth of the two lasers was less than 1 Hz. Utilizing these laser beams, we realized the coherent manipulation of atomic wave packets in an Mach-Zehnder type atom interferometry.

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# Improvements of the statistical and systematic uncertainty contributions of PTB's fountain clocks

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For many years PTB's fountain clocks CSF1 and CSF2 are utilized as primary frequency standards for TAI (Temps Atomique International) steering contributions, the steering of UTC(PTB), the basis for legal time in Germany, and for optical frequency measurements. To date, in a number of concurrent measurements both fountains have demonstrated agreement at the few $10^{-16}$-level within their combined uncertainties. Recently, for further improvements, particular attention has been concentrated on a more rigorous evaluation of frequency shifting effects due to microwave leakage, the distributed cavity phase (DCP) and cold collisions. Because the necessary measurements for such evaluations strongly benefit from improved frequency stability, an optically stabilized microwave source has been developed at PTB [1] and now operates routinely.

For CSF1 a complete systematic uncertainty reevaluation has been undertaken and results will be presented in detail. To suppress frequency shifts caused by microwave leakage, an interferometric switch [2] is now employed to switch on the microwave field in the Ramsey cavity only during the atoms' cavity passages. Using a newly developed phase transient analyser, it has been verified that the switch does not induce detrimental phase variations. These investigations and evaluations of the most crucial uncertainty contributions caused by the DCP and cold collisions are supported by the low phase noise of the optically stabilized microwave source and let us expect an overall systematic uncertainty at the low $10^{-16}$-level.

For CSF2, a significant improvement of the loaded and detected atom number, resulting in an important signal-to-noise ratio enhancement, has been achieved by loading atoms from a cold atom beam from a Low Velocity Intense Source (LVIS, [3]). Using an additional laser beam that pumps atoms into a dark state, we obtain another factor of ~2 enhancement of the useful atomic flux, and a frequency instability of $2.7\times10^{-14}(\tau/1s)^{-1/2}$ limited by quantum projection noise. New results of DCP and cold collisions evaluations will be presented together with updates on the CSF2 uncertainty budget, which also gives an overall systematic uncertainty at the low $10^{-16}$-level.

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# Performance of the NeQuick G Iono Model for Single-Frequency GNSS Timing Applications

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GNSS timing is currently used worldwide in critical real-time systems that require precise synchronisation or time-stamping at geographically dispersed sites, such as wireless telephone stations, electrical power grids and financial services. For applications where multiple timing equipment needs to be deployed, it is desirable to use low-cost (normally single-frequency) receivers, often integrated as "smart antenna" units optimized for tower installation. Together with calibration issues, the ionospheric delay is the major limiting factor for accurate timing in single-frequency setups. Increasing demands in cost-saving and accuracy will make the availability of precise single-frequency solutions more and more interesting.

GPS provides the simple, low-accuracy Klobuchar model, implemented in virtually all GNSS receivers nowadays. For Galileo, the European Union has recently published a detailed description and implementation guidelines for the NeQuick G user model [1]. NeQuick G is designed to reach a correction capability of at least 70% of the ionospheric code delay (RMS). In NeQuick G, real-time iono predictions are based on a single input parameter, the Effective Ionisation Level, *Az*, which is determined using three coefficients broadcast in the navigation message. The Galileo constellation already broadcasts these coefficients.

In this paper we analyse the single-frequency timing accuracy using the NeQuick G model, as compared with the Klobuchar model, and taking the dual-frequency iono-free solution as reference. The study is based on post-processing of pseudorange measurements and navigation messages in RINEX 3 format from two GNSS receivers, located at PTB and connected to the highly stable UTC(PTB) timescale. The receivers have been fully calibrated for the GPS delays in L1 and L2, and for the Galileo delays in E1, E5a, and E5b. Hardware calibration is important in iono model characterization for timing, since the uncorrected iono delay might introduce not only a higher timing noise but also an additional non-zero net delay.

In this study we consider two scenarios: GPS-only, and Galileo-only. Although the NeQuick G parameters are broadcast by Galileo, the model can be applied to GPS measurements as well. The basic PVT solution (Position, Velocity, Time) provides the receiver clock, i.e., UTC(PTB), versus GNSS system time (GPS Time or Galileo System Time). The GNSS navigation messages contain the predicted offset between their respective system time and UTC. Adding this offset to the clock solution from PVT we can then obtain and evaluate the differences between UTC from the two navigation messages and UTC(PTB).

Unlike the Klobuchar model, NeQuick G is based on a rather complex mathematical algorithm. For offline applications in post-processing this is not an issue, but for a real-time implementation inside the receiver it might be necessary to evaluate the model not too frequently, in order to save computing resources. Thus, we study the NeQuick G performance also from this point of view.

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# Narrow-linewidth, micro-integrated UV laser system for precision spectroscopy applications

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

The local oscillator is built around a master oscillator (MO) power amplifier (PA) laser with an extended cavity diode laser (ECDL) as MO and a ridge-waveguide amplifier (RWA) as PA. Results of the optimization of the ECDL are presented, whereby intrinsic linewidths < 1 kHz (in 10 µs timescale) and a side mode suppression ratio > 50 dB over a complete mode-hop free tuning range > 5 GHz are achieved. With the RWA as PA, output powers of the MOPA in excess of 1 W prior to fiber coupling are expected. Moreover, the micro-integration of the MOPA laser into a hermetically sealed package with a footprint of 125 x 75 mm², including low frequency (LF) and high frequency (HF) electrical interfaces, fiber optical interface and integrated thermal management, shall be presented. All materials and processes used for the local oscillator laser are either already space qualified or space compatible.

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

# Improvements in the NPL Primary Frequency Standards System

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A system of two primary frequency standards (caesium fountains) is being developed and integrated with the time and frequency dissemination infrastructure at the National Physical Laboratory. Two fully functional and evaluated standards would provide the minimum redundancy required for the system and allow for in-house comparisons. Short-term stability of the fountain standards is improved by implementation of a high stability microwave source based on an ultra-stable laser and an optical frequency comb transferring the stability to the microwave domain. The output data from the fountains measuring the frequency of a local clock (e.g. a hydrogen maser) will be used for frequent steers of the step interval of the local timescale.

One primary standard, NPL-CsF2 [1], has been in operation for nearly 8 years and upgrades are being planned for some of its subsystems, in particular the electronic control and the optical bench. For the latter, a prototype compact system has been developed and built; it consists of two modules: a laser source module, including saturated spectroscopy for laser frequency stabilisation and a power splitter module for frequency and intensity control of all the beams delivered to the fountain physics package.

A second caesium fountain, NPL-CsF3, is now operational and a preliminary accuracy evaluation has been performed. The results are being validated and will be reported at the conference. For NPL-CsF3 run with the laser based local oscillator a high signal-to-noise ratio and short-term stability below $4 \times 10^{-14}$ (1 s) has been demonstrated. The new local oscillator is currently being optimised and integrated with the fountains' system.

The type B fractional frequency uncertainty of both NPL caesium fountain standards is expected to be marginally above $10^{-16}$. An effect that may hinder reaching accuracy at this level is a possible frequency shift due to microwave phase transients of micro-radian size, which might be synchronous with the fountain cycle. In order to detect and, if necessary, eliminate such an effect a triggered phase analyser has been built following the approach of [2] and using a commercially available digital lock-in amplifier.

In the long-term the aim is to operate the primary standards system semi-continuously for regular contributions to TAI evaluations and, at the same time, for enhancing the stability and accuracy of the local realisation of UTC. The fountain data will also be used in proposed European clock comparison campaigns and during the ACES mission.

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

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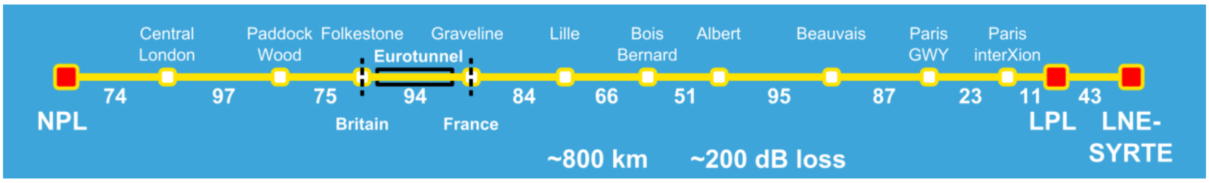
Remote optical clock comparisons are an essential step towards a possible redefinition of the second. However traditional satellite-based techniques lack the accuracy and stability needed. Optical frequency transfer through long haul fiber links has been established as an alternative, and transfer techniques are nowadays mature enough to enable remote optical clock comparison [1-3]. Using these techniques, we aim at performing an international comparison of the clocks developed at SYRTE and NPL, by measurement of the frequency ratio of their atomic transitions. The two laboratories are linked by about 800 km of optical fiber, mostly provided by the pan-European Research and Education network GÉANT. We present our experimental setup that employs a novel hybrid topology combining active compensation and two-way technology, and a new implementation using a repeater laser station at the pivot point.




We present a characterization of the residual phase noise using loop-back measurements over the fiber pair and demonstrate ultra-stable laser comparisons between NPL and SYRTE. Optical clock comparisons are planned for the near future. Together with the link between France and Germany [3], the London-Paris link will allow simultaneous multiple clock comparisons, precise characterization of the European grounds clocks of the ACES mission, and chronometric leveling of the geoid between UK and Europe.

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

# Continuous cold-atom inertial sensor with 0.9 nrad.s$^{-1}$ rotation stability

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We report the operation of a cold-atom inertial sensor in a joint interrogation scheme, where we simultaneously prepare a cold-atom source and operate an atom interferometer (AI) in order to eliminate dead times. This is illustrated in Fig. 1. Dead times and noise aliasing are consequences of the sequential operation which is intrinsic to cold-atom AIs. Both phenomena have deleterious effects on the performance of these sensors. We show that our continuous operation improves the short-term sensitivity of AIs, by demonstrating a record rotation sensitivity of 90 nrad.s$^{-1}/\sqrt{\text{Hz}}$ in a cold-atom gyroscope of 11 cm$^2$ Sagnac area. We also demonstrate a rotation stability of 0.9 nrad.s$^{-1}$ after $10^4$ s of integration, improving previous results by an order of magnitude [1-3]. We expect that the continuous operation will allow cold-atom inertial sensors with long interrogation time to reach their full sensitivity, determined by the quantum noise limit.

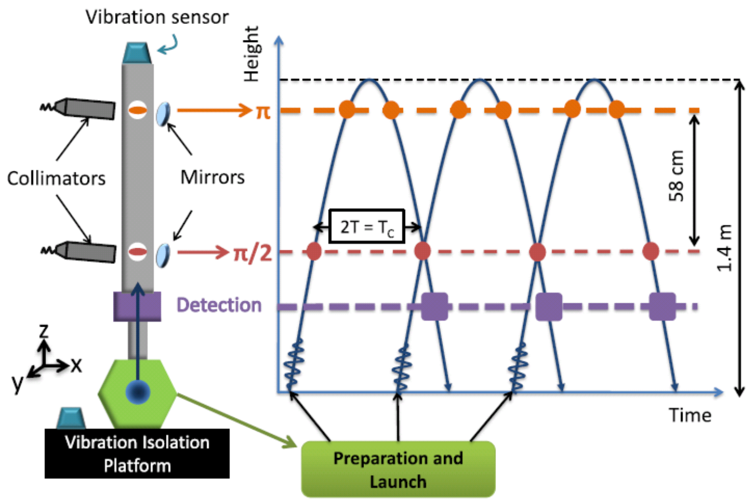


Fig. 1: Schematic and operation principle of the continuous cold-atom gyroscope. Continuous measurement is performed with a joint interrogation sequence where the bottom $\pi/2$ pulse is shared between the atomic clouds entering and exiting the interrogation zone.

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# A Paper Clock Prediction Model for UTC(TL)

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The national standard time and frequency of Taiwan, UTC(TL), is steered according to the BIPM Circular T monthly report in order to let UTC(TL) as close UTC as possible. As the windows period of the BIPM Circular T monthly report may be as long as 45 days, a modified paper clock timescale weighted after removing the linearized frequency drift of each cesium clock in TL's 12-cesium-clock ensemble is used to be the mid-term prediction reference before the next coming announcement of BIPM Circular T. To make the paper clock timescale as stable as possible, we firstly investigated the noise patterns of each cesium clock (Microsemi 5071a with high performance tube) in ensemble and found after removing the linearized frequency drift, their noise were dominated by white noise when the average time was less than 30~40 days. Therefore we could average all clocks to get a relative stable paper clock within the average time less than 30~40 days. To use most of the clocks in ensemble and filter out unstable clocks, we also developed an inversely exponential weighting procedure[1][2] which weighted each cesium clock according to the inversely exponential function of their Allan deviation; therefore the weight of each cesium clocks in ensemble was approximately equal and had a rational upper limit. A steering strategy using both proportional and derivative control algorithm would let UTC(TL) toward the paper clock time scale during the UTC announcement window period. For our 12-cesium-clock ensemble, the phase error of the modified paper clock time scale is less than 10 ns in 45 days.

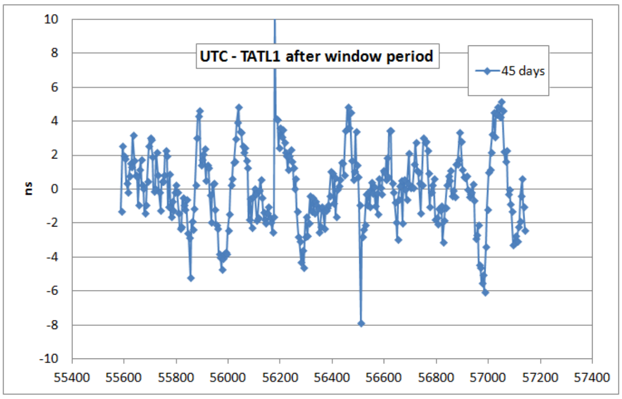


Fig. 1: The 45 days prediction results of time scale $TA_1$(TL) vs. UTC. Prediction error was less than 10 ns in 600 days testing period

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# Investigation on Porous Materials for Cesium Beam Frequency Standard in Space Environment

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Porous materials inside cesium oven play a significant role in enhancing performance of cesium beam frequency standard, such as working lifetime of cesium beam tube, frequency stability of cesium atomic clock and so on. Compared with ground conditions, cesium atomic clock always withstands grim vibrations-mechanical in space environment. In this case, as structural failure, cesium droplets [1] outflowing from liquid dispenser will affect the quality of cesium atomic beam. As shown in Fig.1, based on design principle of spill-resistant oven, the function characteristic of three kinds of porous materials were investigated in theories and experiments respectively, in order to suppress fatigue failure under simulated space environments. In detail, using capillary wetting theory in microgravity, it was analyzed that the anti-spill mechanism on how super-hydrophobic (water contact angle>$90^o$) surface of stainless steel mesh-wire and collimator can avoid liquid cesium to spill from orifice of heat oven. Meanwhile, the experiments of cesium absorption on graphite and of random vibration (RMS>14g) for cesium oven were carried out, for the sake of the availability of cesium frequency standard in space environment. Furthermore, a new notional strategy which depends on extraordinary structure of porous wick with different zone-properties is able to trap the droplets under vibration conditions, and can provide one possibility for potential application in anti-spill technology of space-borne atomic clock.

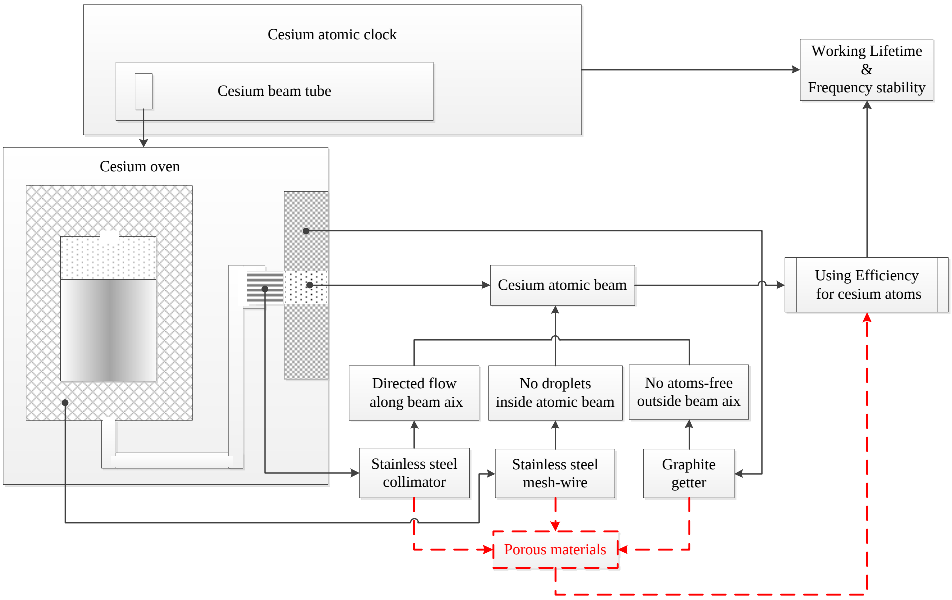


Fig. 1 Relationship between porous materials inside cesium oven and cesium frequency standard

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# Effects of Microwave Leakages on the Frequency Shift of Compact Magnetic Selection State Cesium Atom Clock

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In compact magnetic select state cesium atom clock, the cesium atoms ideally are subjected to microwave field resonant during the two pulses of Ramsey's separated oscillatory field, and arise from the atom transition. As a practical matter, the microwave leakages can be present near the interaction regions along the axis of the beam, which would cause the frequency shift in the cesium atom clock. In order to analyze the effect of the microwave leakages on the frequency shift of the cesium atom clock, this paper discusses the relationship between the leakages in the different positions and frequency shifts. The relational curves of microwave leakage parameters (including the intensity of radiation field, intensity of leakage and length of leakage) versus relative frequency shift would be obtained. The theoretical results show that the leakage taken place outside the interaction area is the one of key reasons to the frequency shift. With the same parameters, the influence of the leakage occurred inside of the interaction area is three order of magnitude smaller than the outside. This result has significantly theoretical significance in evaluating the accuracy of cesium atom clock.

This work is supported by the National Natural Science Foundation of China(Grant No.61471183, 51304100 and 11204116)

# Towards operational sub $10^{-16}$ frequency transfer with IPPP

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Since many years, GPS phase and code observations have provided reliable time and frequency transfer between stations whatever their location on Earth. The technique of choice is Precise Point Positioning (PPP), with a typical uncertainty for frequency comparisons of order $1 \times 10^{-15}$ at 1-day averaging and a few $10^{-16}$ at 5 to 10 day averaging.

One approach to overcome the limitations of "classical PPP" is to consider the integer nature of phase ambiguities. The CNES-GRGS group pioneered this technique and is now an IGS analysis center providing satellite products that allow applying integer ambiguity resolution to PPP [1]. This IPPP technique allows frequency comparison at any distance over long durations and we have shown [2] that a frequency transfer accuracy of $1 \times 10^{-16}$ is reached at ~3 to 5-day averaging for regional links. Furthermore the performance of IPPP frequency transfer should continue to improve as the inverse of the integration time as long as the two receiving systems are not perturbed by discontinuities. Fig. 1 illustrates this result for the 270-km link between two time laboratories in Poland: AOS in Borowiec and GUM in Warszawa. A similar performance is likely achievable for long distance links but cannot be tested for lack of an accurate reference.

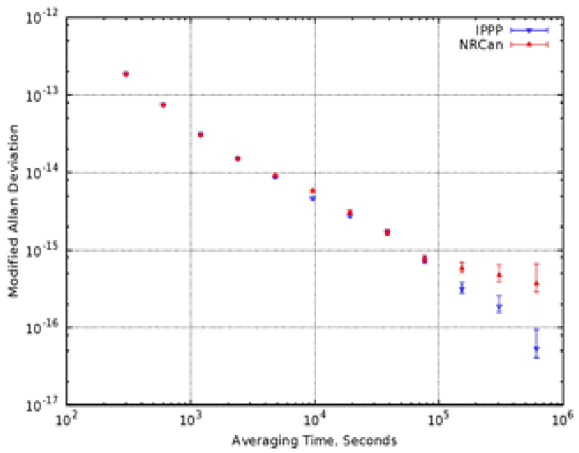


Fig. 1: Stability analysis for the comparison between a 420-km optical fibre link and the results obtained with IPPP (blue) and classical PPP (red) over 41 days.

The BIPM recently implemented test IPPP computations as an additional technique in its database of link comparisons ftp://tai.bipm.org/TimeLink/LkC/. As experience is gained, procedures necessary for the IPPP computation are being improved at all stages of the process: the generation of satellite products, the estimation of integer ambiguities on daily batches and the final connection of the links. Recent time and frequency transfer results using IPPP will be presented.

While regional frequency comparisons will be performed with unprecedented accuracy using fiber links, no perennial technique is on the horizon for long distance links. It is thus important to gain as much as possible from the established GNSS techniques.

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# Towards sub-nanosecond synchronization of a telecom network by fiber optic distribution of UTC(k)

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To guarantee the robust synchronization for several 10-thousand telecom base stations, an advanced, hierarchical synchronization supply network is needed. For state-of-the-art core-level synchronization of the ensemble of enhanced Primary Reference Time Clocks (ePRTC), a maximum absolute time error below 30 ns is required. However, from the network operator's point of view, some meta-level of synchronization is needed for reliable monitoring and assessment of the actual performance of ePRTCs, and to prevent (or localize) possible synchronization issues. At this meta-level the synchronization accuracy should be at the single nanosecond level, and as an option, could be referred to a particular UTC realization.

In this work we present first results of delivering UTC(PTB) (1 PPS and 10 MHz) by optical fiber to a test center of Deutsche Telekom in Bremen. The work done focused on a proof-of-concept in a real telecommunication environment and the demonstration of the long-term operations capability and scalability of the approach. We use ELSTAB time and frequency (T&F) distribution technology with an active propagation delay stabilization [1].

The measurements started in July 2015 and are performed in parallel using the methods and means typical for telecom operators, and common in the T&F metrology domain. As no superior clock is currently operated in Bremen, the T&F signals are temporarily send back to PTB for the evaluation of transfer stability and accuracy. The link consists of a 220 km-long fiber feeding a "slave" terminal at a DTAG center in Bremen and another 220 km of fiber back to a second "slave" terminal at PTB. The "slave" terminals reproduce the incoming 1 PPS and 10 MHz signals. In Fig. 1 we show the results of a stability analysis of the "slave" signals at PTB with respect to the outgoing signals, using a time interval counter for the 1 PPS signals and a phase measurement system with higher resolution at short averaging times for the 10 MHz signals.

The four months-long continuous observations and measurements let us conclude that the synchronization significantly below 1 nanosecond between a UTC laboratory and a telecom center may be obtained using existing standard fiber infrastructure of a telecom operator.

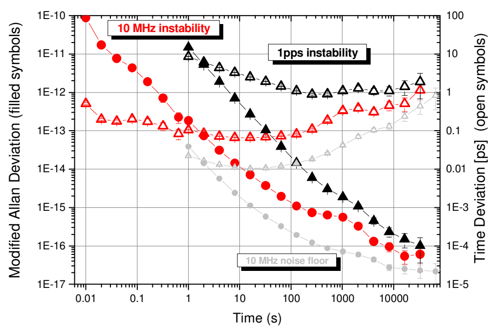


Fig. 1: Stability analysis of ELSTAB output signals of the slave module operated at PTB at the end of the 2x220 km loop; time domain (open symbols, right scale) and frequency domain (full symbols, left scale); 1 PPS signals (black), 10 MHz signals (red), and 10 MHz noise floor (gray).

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# Realization of a timescale with an optical clock

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Due to their unprecedented stability and precision optical clocks are commonly considered the future of timekeeping. So far, optical clocks, however, are not reliable enough due to their complexity, which then again is typically regarded detrimental to the continuous and precise ticking of a timescale. Here, we show that a single conventional maser flywheel is enough to bridge substantial down-times of a Sr optical clock and, yet, achieve a performance surpassing that of today's best timescales based on fountain clocks even if the they were operated continuously.

Due to the lack of a suitable reference timescale for an experimental characterization, we choose a numerical approach based on a real 12-days measurement campaign in October 2014 to demonstrate the performance of a real-time timescale TS(Sr) steered by the Sr clock (see Fig. 1; overall clock availability: ≈ 30%, interruptions over weekend). We numerically generate a continuous maser frequency data trace $y_H$ and a Sr trace $y_{Sr}$ for the given up-times to compute TS(Sr). The traces reflect the properties of the respective oscillator achieved at that time [1]. Moreover, we provide a complete mathematical analysis of the predictability of TS(Sr) via its uncertainty, that is dominated by the contribution coming from the use of the maser flywheel to bridge clock down-times. This is compared to the uncertainty of a theoretical timescale TS(Cs) based on a Cs reference with 100% up-time (assuming the parameters of PTB's fountain clock CSF2 [2]).

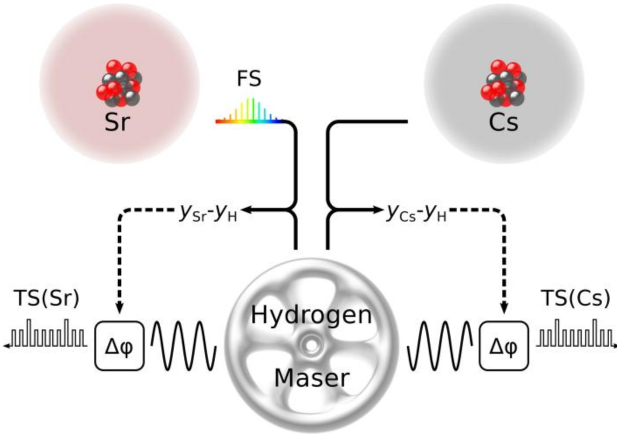


Fig. 1: Realization of a timescale TS from a microwave and an optical clock: The Cs clock transition frequency is compared against the maser flywheel frequency. The acquired offset $y_{Cs} - y_H$ is used to generate the classical timescale TS(Cs) generated from the maser utilizing a phase stepper (Δφ). An equivalent scheme is applicable when referencing the timescale TS(Sr) to an optical frequency standard. For that purpose, the clock laser light is down-converted to the microwave regime using a femtosecond frequency comb (FS) before comparing against the flywheel.

We demonstrate how PTB's strontium lattice clock is able to maintain a local timescale with a time error of less than 200 ps compared to an ideal reference over about 12 days, or $1.6 \times 10^{-16}$ in fractional frequency. Thus, TS(Sr) surpasses the performance of the Cs referenced timescale by more than a factor of two [1]. We will discuss further improvement of the optical timescale with even higher clock availabilities and a more elaborated choice of flywheels.

This work was supported by the DFG through the RTG 1729 and the CRC 1128 geo-Q and the ITOC & QESOCAS projects, which are part of the EMRP.

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# Frequency synthesis from cryogenic sapphire oscillator

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The FEMTO-ST Institute, Besançon, France and the French space agency (CNES), Toulouse, France investigate the origins of noise in bulk acoustic wave resonators for several years [1]. To characterize ultra-stable resonators, the passive technique with carrier suppression is used to measure the inherent phase stability of the ultra-stable resonators. This kind of bench usually uses both identical resonators inserted in each arm in order to suppress the noise of the source [2]. To operate with only one resonator, the driving source must have a phase noise lower than the best resonators that are measured.

At 5 MHz, the power spectral density of phase fluctuations of these best quartz crystal resonators is expected around -140 dBc/Hz. In these conditions, the driving source cannot be an ultrastable 5 MHz quartz oscillator. Cryogenic sapphire oscillators present a very low phase noise [3]. Thus in this paper, first results of frequency synthesis chain from cryogenic sapphire oscillator are presented. A 100 MHz signal is divided until 5 MHz in order to get the best phase noise. Several divider combinations are presented and discussed. The limits of commercial dividers are shown and best results have been obtained using regenerative dividers (Fig. 1). Further investigations are proposed in order to improve these results.

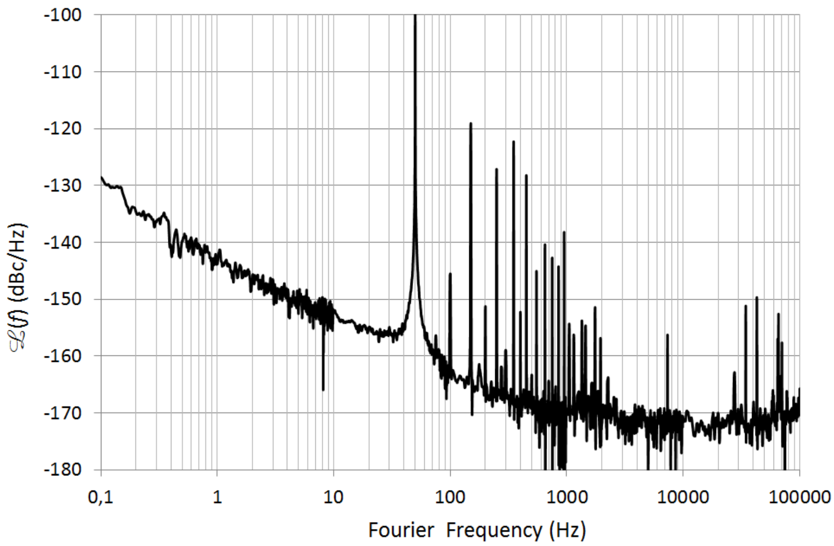


Fig. 1: Phase noise of 5 MHz signal generated from 100 MHz cryogenic sapphire oscillator.

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# Pilot Comparison of Time Interval Measurements with High Speed Oscilloscopes – initial results

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In this paper we present the initial results of the pilot comparison of time interval measurements with high speed oscilloscopes being the part of the EURAMET Project #1288, coordinated by MIRS/SIQ. This comparison is aimed to better characterise the developed by AGH and GUM electronic based Time Interval Generator (TIGen) as a time interval standard for a new Inter-Laboratory Comparison planned as a Supplementary Comparison in the KCDB.

So far, the obtained results for TIGen confirm the stability of generated time intervals at the single picoseconds level, but the absolute values of the generated time intervals have not yet been compared between different institutes. At the same time, high speed oscilloscopes are considered to be ones of the most accurate instruments for precise measurements of short time intervals. So, this pilot comparison is also able to verify and confirm the metrological quality of TIGen as well as additionally to verify and confirm the metrological equivalence of high speed oscilloscopes for absolute time interval measurements.

Relatively small group of participants in this comparison includes some NMIs or DIs (SIQ, UME, SASO) and research institutes operating in time and frequency domain (AGH, NIT) and were limited to close the comparison in a few months. GUM is responsible for coordinating the schedule, collecting and analysing the comparison data and preparing the report.

The previous experience with a cable delay measurements within the EUROMET Project #828 showed that a cable delay is not well-defined measured quantity and its value is significantly dependent on the shape of signals used for cable delay measurements and the selected trigger levels. For the cable delay of about 175 ns (the cable length of about 35 m), the values of obtained results (estimates) were scattered within the range of about ± 1 ns.

In this comparison, the results are matched very well and contained within the range less than ± 10 ps around each measured value of time interval – up to about 12 µs, if the oscilloscope were synchronized to the external reference frequency. At the conference we plan to show some details of the used time interval standard and the applied methods as well as discuss the obtained agreed results in a poster form. A such investigations are very important for precise time interval measurements, especially at calibration of different methods of precise time transfer.

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# UV laser system for Rydberg spin-squeezing in a strontium optical lattice clock

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Optical lattice frequency standards have demonstrated world leading fractional frequency instabilities and uncertainties [1]. The fractional frequency instability is currently limited by the Dick effect, and the best clocks demonstrate instabilities within a factor of 3 of the quantum projection noise (QPN) limit [1,2]. Interleaved interrogation methods have been proposed to lower the Dick effect beyond the QPN limit and may soon be realized [2]. Our proposal uses the strong van der Waals interactions between Rydberg atoms to provide a high degree of spin-squeezing to overcome the QPN limit in optical lattice clocks [3]. It requires the addition of one extra laser to the strontium lattice clock set-up, and here we present a UV laser system built for such a purpose [4].

We have developed a high power, widely tunable, narrow-linewidth UV laser system for Rydberg excitation and dressing in strontium atoms [4]. This laser has over 5 THz of tuning range, providing access to a wide range of Rydberg states from both the 5s5p $^3P_1$ and 5s5p $^3P_0$ intermediate states. We measure the long-term frequency instability of the laser on a GPS-referenced optical frequency comb to be <35 kHz, and can make absolute frequency measurements of the Rydberg transition line centres with a precision of <5 kHz. Rydberg spectroscopy in a cold atomic sample reveals Voigt-shaped profiles, with Doppler limited linewidths of 350 kHz. We present the design and characterisation of the laser system, along with experimental progress towards Rydberg dressing strontium atoms - a key step for the implementation of this spin-squeezing protocol.

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# Thin film viscoelastic losses of a length extension mode resonator

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In order to guarantee high stability of time and frequency resonators each new design must be thoroughly optimized to reduce losses and maximize the quality factor per frequency product Q.f. The quality factor can be described as the sum of intrinsic and external losses:

$$\frac{1}{Q_{tot}} = \frac{1}{Q_{anchor}} + \frac{1}{Q_{air}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{AKE}} + \frac{1}{Q_{visc}} \quad (1)$$

We presented in a previous paper [1] a new length extension mode (LEM) piezoelectric micro-resonator, consisting in two beams vibrating in length extension out of phase from the main central beam. We focused on anchor losses and temperature sensitivity regarding quartz cuts [1], to evidence its potential for time and frequency applications. Assuming the Q.f intrinsic product for quartz is very close to $3.10^{13}$ [2] and considering Akhiezer losses ($1/Q_{AKE}$) as a limit, we demonstrated with finite element that thanks to a specific design allowing $Q_{anchor}>10^8$, and a maximized Q.f product. Viscous fluid damping is negligible ($1/Q_{air}$), since the resonator is held under vacuum and so is the thermoelastic damping ($1/Q_{TED}$) for a length extension mode, it appears that viscous damping $1/Q_{visc}$ arising from the gold electrodes thin film is the only remaining loss. In [3], the behavior of gold electrode is described using a Kelvin Voigt model. Assuming the same theory for our length extension resonator and considering electrodes cover the whole surface of the central beam an analytic approximation of this quality factor is:

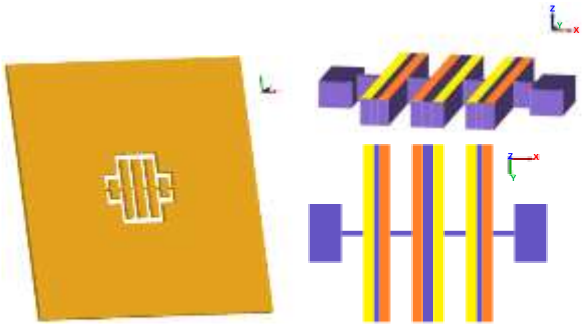

Fig. 1: 2D LEM resonator structure (on the left) basic electrode configuration for a Z quartz cut on the right.

$$Q_{visc} = \frac{2\pi W_{stored}}{W_{lost}} = \frac{E_{Quartz} h_q}{\eta\omega 2 h_e} \quad (2)$$

Which gives $Q_{visc} \sim Q_{tot} = 8123$ for a resonator at a frequency of 1.3 MHz ($E_{quartz}$ : quartz Young modulus, $h_q$ : quartz thickness, $h_e$ : electrode thickness, $\eta$ :gold viscosity deduced form [3] at 8.8 kHz). Nevertheless, similar LEM resonators have been formerly studied in [4] assessing a $Q_{tot}$=340 000 for a 1.2 MHz resonator. From this consideration a study is being carried out on new electrode designs to reduce viscoelastic damping finding a compromise between motional resistance and quality factor and to improve the viscoelastic modeling of gold electrodes.

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# The 2015 TWSTFT calibration for UTC and related time links

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Two-Way Satellite Time and Frequency Transfer (TWSTFT or TW) is one of the primary time transfer techniques for UTC generation. Calibration is one of its key strengths, but it requires considerable investment in staffing, time, and funding. As a practical matter, only the links used in the calculation of UTC i.e. the TW links between laboratories and the pivot laboratory (the PTB at present) need to be calibrated. These are a small part of the total possible links in TW network. Some laboratories make use of TW time comparisons for applications other than UTC computation. In these cases the Triangle Closure Calibration (TCC) technique provides an opportunity to calibrate these links without direct use of a TW mobile calibrator.

The concept of the triangle closure condition in a TW network was proposed in 2005 [1], and in 2008 the first TCC calibration in the TW network was performed [2]. The TCC method has been applied recently to the calibration of non-UTC links of six laboratories in Europe and the US, whose links with the PTB were calibrated with TW or GPS mobile stations [4-7]. In September 2015, at the 20th meeting of the Consultative Committee for Time and Frequency (CCTF), the TCC was reported as a method for achieving TW link calibrations, and it was included in the TW calibration guidelines approved by the CCTF Working Group on TWSTFT.

The principle of the TCC is simple: 1) Two UTC TW links Lab(A)-PTB and Lab(B)-PTB are assumed to have been calibrated with either a TW or a GPS mobile calibrator with known uncertainties; 2) The calibration correction of [Lab(A)-Lab(B)] is determined by the requirement that, after the known calibrations are applied to the PTB links, [Lab(A)-PTB]-[Lab(B)-PTB]+[Lab(B)-Lab(A)] must be zero. The uncertainty ($u_B$) is determined by the root sum square (RSS) of the uncertainties of the two PTB link calibrations along with the closure measurement's precision.

We first introduce the latest UTC TW link calibrations [3-7] and then a rapid review of the TCC method is presented, followed by the results of the 2015 TCC calibration computation with the uncertainty evaluation. Finally, we discuss the comparison between parallel TW and the GPS time links that have been calibrated independently in the recent years.

Key words: TWSTFT or TW, TCC, Calibration, Uncertainty, TW Network, CALR

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# A high-performance CPT-based Cs vapor cell atomic clock using push-pull optical pumping

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**To be considered for student competition**

Microwave vapor cell atomic clocks are exciting candidates for numerous timekeeping applications because they combine compactness, a modest power consumption and excellent fractional frequency stability at the level of a few $10^{-13}\ \tau^{-1/2}$ [1,2,3]. In the frame of the MClocks project funded by EURAMET, we report on the development of a Cs vapor cell atomic clock based on coherent population trapping (CPT).

The optics part of our clock combines a distributed feedback (DFB) diode laser resonant on the Cs $D_1$ line at 894 nm, a pigtailed Mach-Zehnder electro-optic modulator driven at 4.596 GHz, an acousto-optic modulator (AOM) and a Michelson-based delay line and polarization orthogonalizer system. The laser is frequency-stabilized on an annex Cs vapor cell using a dual-frequency saturated absorption scheme at the output of the EOM. The optics ensemble allows to produce the so-called push-pull optical pumping (PPOP) scheme [4,5] leading to the detection of high-contrast CPT resonances on the clock transition. CPT interaction occurs in a 2-cm diameter and 5-cm long Cs vapor cell filled with a $N_2$-Ar buffer gas mixture of total pressure 15 Torr. The typical clock resonance signal exhibits a contrast of about 25% and a linewidth of 400 Hz.

The clock, in continuous regime, has demonstrated a short-term fractional frequency stability at the level of 3 $10^{-13}\ \tau^{-1/2}$ for integration times up to 100 s [6]. These performances, among the best performances ever reported for a CPT-based clock, were recently improved to reach routinely 1.8 - 2 $10^{-13}\ \tau^{-1/2}$ for integration times up to 100 s. The short-term stability is mainly currently limited by laser intensity effects and the Dick effect. The mid-term frequency stability is limited by light-shift effects.

Different aspects will be investigated towards the conference to improve the clock performances: the use of a newly-designed ultra-low phase noise frequency synthesizer to reduce the Dick effect contribution [7] and the implementation of dedicated laser power noise reduction techniques. Additionally, preliminar tests of a Ramsey-like interrogation scheme of the clock transition for reduced sensitivity of the clock frequency to laser intensity variations will be performed. Latest results will be presented at the conference.

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# A HBAR-oscillator-based 4.596 GHz frequency source: design, characterization and application to a Cs microcell atomic clock

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The most common technological approach for the development of a local oscillator in miniature atomic clocks (MACs) application consists of a frequency synthesizer using a LC voltage-controlled oscillator (VCO) phase-locked to a 10 MHz quartz oscillator through a fractional-N phase-locked loop (PLL) [1,2]. However, in such systems, the frequency multiplication degrades the phase noise and can consume up to 50% of the MAC total power budget [1]. In that domain, a promising alternative solution is the development of microwave MEMS oscillators based on bulk acoustic wave (BAW) resonators, exhibiting small size, low power consumption and high Q-f products.

This work reports on the design and characterization of a high-overtone bulk acoustic wave resonator (HBAR)-oscillator-based 4.596 GHz frequency source. A 2.298 GHz signal, generated by an oscillator constructed around a thermally-controlled two-port AlN-sapphire HBAR resonator with a Q-factor of 24000 at 68°C, is frequency multiplied by 2 to 4.596 GHz, half of the Cs atom clock frequency. The temperature coefficient of frequency (TCF) of the HBAR is measured to be -23 ppm/°C at 2.298 GHz. The measured phase noise of the 4.596 GHz source is -105 dBrad$^2$/Hz at 1 kHz offset and -150 dBrad$^2$/Hz at 100 kHz offset. These phase noise performances are significantly better than those achieved with usual technologies [1,2].

The 4.596 GHz output signal is used as a local oscillator (LO) in a laboratory-prototype Cs microcell-based coherent population trapping (CPT) atomic clock [3]. The HBAR-based source signal is frequency-stabilized onto the atomic transition frequency in two steps: a coarse frequency tuning by adjusting the HBAR resonator temperature and a fine tuning by using a voltage-controlled phase shifter (VCPS) implemented in the 2.298 GHz HBAR-oscillator loop, preventing the need for a high-power-consuming direct digital synthesis (DDS).

The short-term fractional frequency stability of the free-running oscillator is 1.8 $10^{-9}$ at one second integration time. In locked regime, the latter is improved in a preliminary proof-of-concept experiment at the level of 6.6 $10^{-11}$ $\tau^{-1/2}$ up to a few seconds and found to be limited by the signal-to-noise ratio of the detected CPT resonance. The potential of this technology to be embedded in viable miniature atomic clocks will be discussed.

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# A novel alkali vapor microcell architecture for miniature atomic clocks

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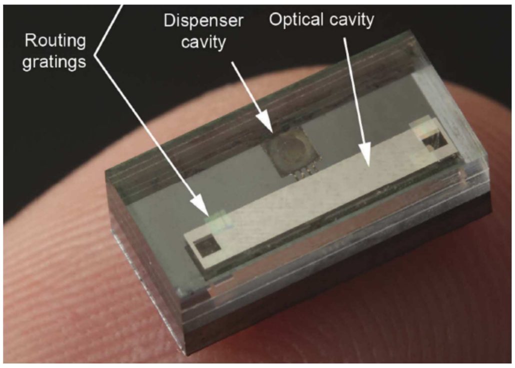
Numerous efforts in different laboratories and companies have been accomplished towards the development of miniature atomic clocks [1,2]. The heart of a MAC is a microfabricated alkali vapor cell, generally filled with a pressure of buffer gas. In FEMTO-ST, we have proposed an original microcell technology in which the Cs vapor is generated after complete sealing of the cell using laser activation of a Cs pill dispenser [3]. This technology is now well-mature and started an industrial transfer process.
In the same time, we met in past projects some potential issues towards an easy and comfortable assembling and alignment of respective components (VCSEL laser, microcell, optics, etc.) of a complete MAC physics package.
In that sense, we report in this work a new and original architecture of microfabricated alkali vapor cell designed for miniature atomic clocks. The Cs filling procedure is still based on laser activation of a Cs pill dispenser. The cell combines diffraction gratings with anisotropically etched single crystalline silicon sidewalls to route a normally-incident beam in a cavity oriented along the substrate plane. Gratings have been specifically designed to diffract circularly polarized light in the first order, the latter having an angle of diffraction matching the (111) sidewalls orientation. The length of the cavity where light interacts with alkali atoms can be extended. As the cavity depth and the beam diameter are reduced, collimation can be performed in a tighter space. This solution relaxes the constraints on the device packaging and is suitable for wafer-level assembly. Several cells have been fabricated and characterized in a clock setup using coherent population trapping spectroscopy. The measured signals exhibit null power linewidths down to 2.23 kHz and high transmission contrasts [4]. Further tests are under progress to characterize the potential of this cell technology. Latest results will be reported at the conference.

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# Cross-spectral Collapse from Anti-correlated Thermal Noise in Power Splitters

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Oscillators enable much of our modern technology, including smart phones, GPS receivers, radar/surveillance/imaging systems, electronic test and measurement equipment and much more. System designers and manufacturers need oscillators with the lowest possible phase noise (timing jitter or spectral purity), especially for high performance applications. But at current high performance (low noise) levels phase noise measurements give varying results, often severely under-reporting phase noise [1]. Fig. 1 depicts the difference between measured and the theoretical thermal phase noise of an ultra-low noise oscillator at 100 MHz measured with the cross-spectrum technique. One cause of this difference as explained in [2] can occur due to the anti-correlation collapse mainly from AM noise leakage. More recently, a different source of anti-correlation in a cross-spectrum measurement has been identified; the origin is from the common-mode power splitter (Wilkinson or resistive). The correlated thermal noise of the power splitter appears equally but in opposite phase in two channels of the cross-spectrum system. We will discuss the effect of anti-correlated thermal noise of various reactive and resistive power splitters on the noise measurement of ultra-low phase noise oscillators.

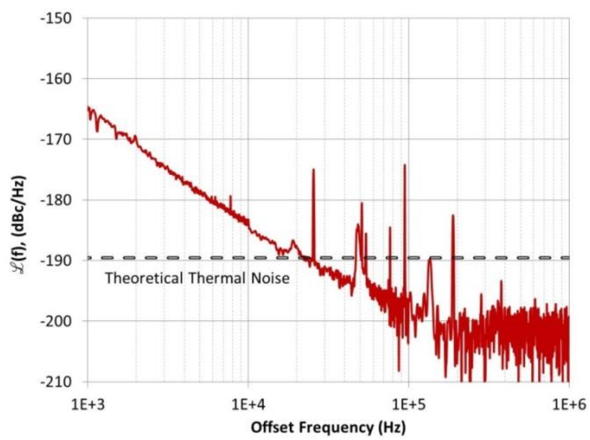


Fig. 1: Phase noise of a 100 MHz oscillator measured with cross-spectrum system. More than 10 dB difference between measured and theoretical thermal phase is observed. The bottom noise plot is limited by the number of FFT averages *N*; for offset frequencies above 10 kHz, *N* = 100,000

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# A Preliminary Prototype of Laser Frequency Stabilization for Space-borne Interferometry Missions

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A prototype of laser frequency stabilization system for inter-satellite laser ranging is presented in this paper. This system used Pound-Drever-Hall (PDH) method [1] to stabilize the laser frequency and hydroxide-catalysis bonding technique [2] to manufacture the Fabry-Pérot (FP) cavity and its mode-matching optical layout on a quasi-monolithic ULE optical bench, whose optical and geometric parameters had been optimized to ensure the mode-matching efficiency and to minimize the vibration sensitivity of the cavity. All-fiber devices were applied for the PDH optical link, and an in-house-designed digital controller was developed for automatic laser frequency locking. Simplified depiction of this system and the photo of the optical bench are shown in Fig. 1(a) and (b). The optical bench was installed in a vacuum chamber with $10^{-7}$ mbar level of pressure and its surrounding temperature was actively controlled within 0.6 mK. Active vibration isolation was used to suppress the seismic noise to $10^{-7}$ g/Hz$^{1/2}$ during demonstration of the prototype on ground.

The digital controller was developed on FPGAs and programmed by LabVIEW® software with self-analyzing functions built in for real-time and closed-loop diagnosis and adjustments [3]. In this controller, abilities of initially locking the laser frequency to the cavity and recovering from an unlocked condition automatically had been developed, which can benefit automatic operations on board. One of the recorded auto-locking processes is shown in Fig. 1(c).

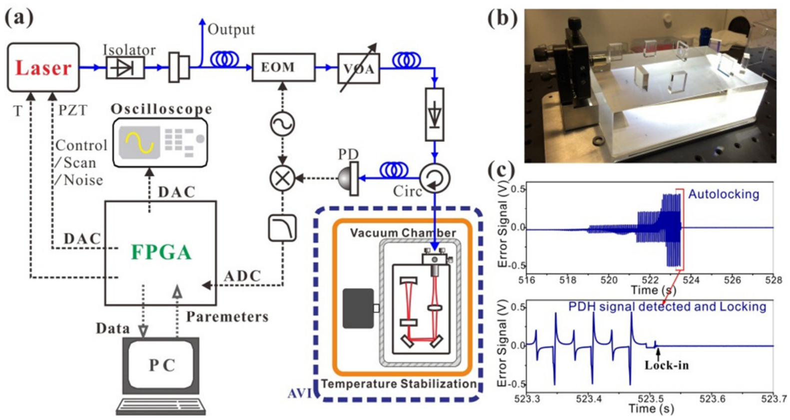


Fig. 1: (a) Simplified system of the laser frequency stabilization prototype; EOM, electro-optic modulator; VOA, variable optical attenuator; Circ, circulator; AVI, active vibration isolation. (b) Photo of the ultra-stable ULE optical bench. (c) Error signal data during a laser frequency auto-locking process.

The frequency stability of the prototype had been studied by beat note with an independent ultra-stable laser at sub-Hz-level stability. Preliminary result shows that the frequency noise of this prototype is less than 30 Hz/Hz$^{1/2}$ from 0.7 Hz to 10 Hz, and is still being improved. Updated results will be presented in the conference.

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# Design of a new calibration device for Two-Way Satellite Time and Frequency Transfer Station

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The Calibration Device is used to measure the time delay difference between transmission and receiving paths inside Two-Way Satellite Time and Frequency Transfer (TWSTFT) earth station, it can improve the time comparison precision. A new calibration device for TWSTFT has been developed recently at Beijing Institute of Radio Metrology and Measurement (BIRMM) .The signal paths inside calibration device is bidirectional which allow both the transmission and receiving signal passed, so the delay difference of the transmission and receiving inside calibration device almost be zero. The calibration device works on Ku-band. To evaluate the performance of the BIRMM calibration device, a local TWSTFT experiments was done with SATRE modem. The measurement results show that the time delay difference was quite small instability with standard deviation (1 σ) equal to 0.17ns.

BIRMM calibration device works in three modes which can be controled by LAN command: TX calibration mode, RX calibration mode and calibration OFF mode. Figure 1 is the block diagram of the calibration system. BIRRM calibration device (green block) include two parts: the outdoor unit and the indoor unit. The time delay of the transmission and receiving path which need to be calibrated is separately shown by the red and green cable. Fig.2 and Fig.3 shows the indoor unit and the outdoor unit.

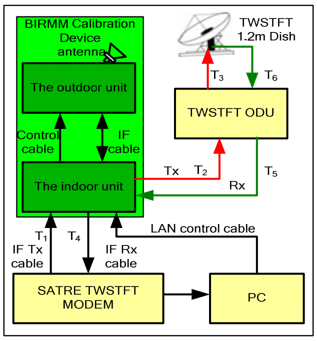


Fig.1: The block diagram of the calibration system.

Fig.2: The indoor unit of the BIRMM calibration device.

Fig.3: The outdoor unit of the BIRMM calibration device.

In order to evaluate the performance of the BIRMM calibration device, a local TWSTFT experiment was done. The devices and the cable connections of the experimental system are illustrated as shown in Fig. 1. The code rate of SATRE Modem is 2.5Mchip/s, and the output power is -25dBm. Then select the measure mode of BIRMM calibration equipment and start measure The measure time is one hour in each mode. Fig.4 shows the outdoor experimental system on a building roof. Fig.5 is the calculated results of [TX-RX] values. The calibration results have an average value of 17.95 ns, and have instability with standard deviation (1 σ) equal to 0.17ns.

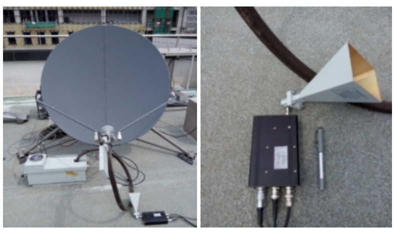

Figure.4: The outdoor experiment system

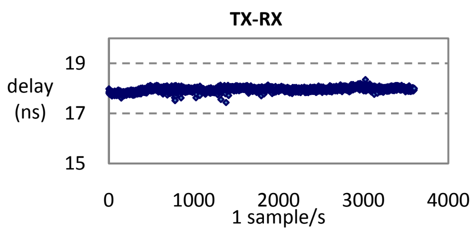


Fig.5: The time delays difference calibration results.

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# Preparation of High Purity Cesium by Molecular Distillation

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A novel technique was developed to purify 99.5% cesium by molecular distillation to meet the stringent requirement of Cesium-Atomic-Clock. The influence of the molecular distillation conditions, including but not limited to the temperature, pressure, rotation speed of the wiper blade and feed-in rate, on the Cs purification was experimentally investigated. The results show that depending on the purification conditions, most impurities of K and Rb were removed. To be specific, under the optimized conditions: a temperature in 490～510K range, a wiper blade rotation speed in 180～210 r/min range, and a feed in rate in 3～5 g/min range, the Cs purity reached 99.95%, accompanied by the removals of K impurity from 690 PPM(Parts Per Million) to 106 PPM and Rb impurity from 840 PPM to 123 PPM. We suggest that the molecular distillation may outperform the conventional vacuum distillation because of a lower temperature and a shorter time.

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# On a Conceptual Error in Cross Spectrum PM Noise Measurements

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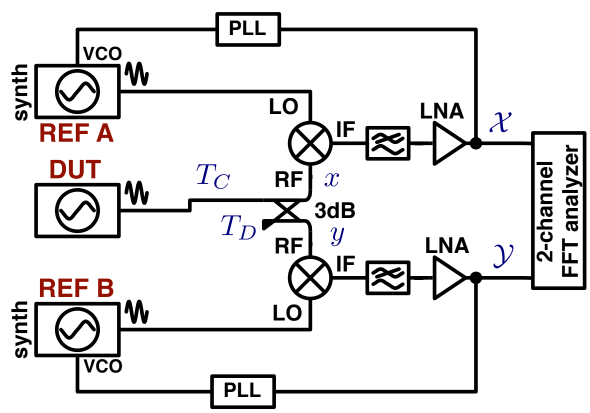
White phase noise can be written as $S_\varphi(f) = kT/P$, where $k$ is the Boltzmann constant, $T$ is the equivalent temperature, and $P$ the carrier power. The extension to parametric noise with $T = T(f)$ is not straightforward because parametric noise is not equally split between AM and PM, and anyway not necessary for our purposes.

Modern instruments use two equal channels and cross PSD to average out the single-channel background (reference oscillator, mixer, amplifier, etc.), as shown in the figure.




In most cases the power splitter at the input is actually a directional coupler terminated at the dark port. Such coupler makes the sum and the difference of the two input signals. It turns out that the cross PSD at the outputs is $S_{yx} = \frac{1}{2}k(T_1 - T_2)$, where $T_1$ and $T_2$ are the temperature of the input loads. This property is commonly exploited in radiometry and in Johnson thermometry. The obvious implication to phase noise is that the displayed quantity is $S_\varphi = k(T_C - T_D)/P$. However, in the laboratory practice the thermal energy $kT_D$ of the dark port is generally not accounted for. There results a systematic error of $-kT_D/P \approx 4{\times}10^{-21}/P$ [rad²/Hz]. Of course, small signal calibration does not address this issue because the 'small signal' is always large compared to the thermal energy.

For example, a raw result of −185 dBc/Hz (−182 dBrad²/Hz) with $P = 13$ dBm gives the equivalent temperature $T_C - T_D = 912$ K. Accounting for a 40 °C temperature of the dark port (inside the instrument), the actual temperature of the oscillator is of 1223 K. In turn, the oscillator PM noise is of −183.7 dBc/Hz (−180.7 dBrad/Hz). However, in the case of a cryogenic oscillator $T_C - T_D$ can be negative and, in the absence of the appropriate correction, the result is a total nonsense.

We provide the formal derivation, and the experimental evidence using an audio-frequency mockup. The reason for this choice is the full control on crosstalk. Our measurement are done in a shielded chamber, with additional magnetic shield on the critical circuits.

# Multi-clock Dissemination via One Ring-like Fiber Network

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Without an ideal clock which can be regarded as an absolute reference, the International Atomic Time (TAI) coordinating hundreds of high precision atomic clock all over the world is generated to keep the time scale supporting global applications from electricity distribution to large-scale of scientific facilities [1]. To link and compare all these atomic clocks, methods of low-loss coaxial cable and satellite have been applied in short and long distance situations. However both of these dissemination methods can no longer satisfy the requirement of the tremendous progress on stabilities of atomic frequency standards. Thanks to the characteristics of ultra-low loss and anti-electromagnetic interference, lots of schemes based on optical fiber have been demonstrated to achieve a higher precision. Whereas, one can only reproduce the frequency from one local station to multiple users using all current schemes [2,3]. That means problem still leaves in multi-clock comparison in one simple fiber link. An "N" to "N" solution is still expected.

In this paper, we present a concept of injecting high precise frequency signals into one stabilized fiber ring-like network to satisfy the requirement of multi-clock dissemination and comparison. Master clock station suppress the noise of the whole fiber link, while slave clock can simply inject the radio frequency signal anywhere along the fiber link. One can recover the multi-clock signals with passive compensation in a recovery station. For an experimental test, two clock stations and a recovery station separated by two 25km fiber spools have been demonstrated in a stabilized fiber loop. Relative frequency stabilities of 3e-14@1s and 5e-17@$10^4$s for master clock and 5e-14@1s and 8e-17@$10^4$s for slave clock are obtained. Detailed experimental results and residual noise analysis will be shown during the conference.

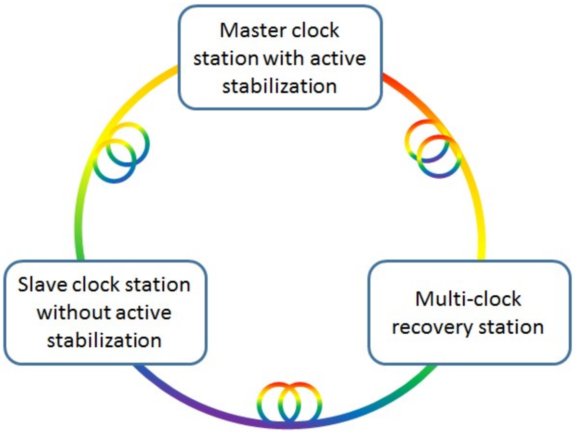


Fig. 1: Schematic diagram of the multi-clock dissemination structure

This work was supported in part by the National Natural Science Foundation of China under Grant 61405227

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# Remote atomic clock delivery to the VLBI station in Toruń

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On 26th Nov. 2015 Toruń Radio Astronomy Observatory (based in Piwnice near Toruń), a part of the Centre for Astronomy of N. Copernicus University, Toruń (Poland), was connected to the Polish fiber optic network distributing time and frequency (T&F) signals from UTC(PL) and UTC(AOS) laboratories – see Fig. 1. This paves the way for investigation of alternative methods of T&F synchronization during Very Long Baseline Interferometry (VLBI) observations. The technology of T&F distribution was developed at AGH University.

Typically, T&F signals for VLBI observations are provided by a local standard, usually an H-maser. Here, we report how the fiber network allows remote synchronization of the station with optical strontium clock operated in Toruń and with both Polish UTC laboratories. Additionally, the local H-maser may be disciplined by these remote sources.

The first proof-of-concept VLBI observation using remote synchronization via optical fiber link was carried out on 18th Dec. 2015. The participating stations were Toruń(PL), Westerbork(NL), Medicina(IT), Yebes(ES), and Onsala(SE). The raw data from the stations were transferred to the Joint Institute for VLBI ERIC (JIVE) and the correlation proceeded in real-time (the e-VLBI technique). Additionally, the raw data from the stations were recorded at JIVE for possible further processing. The T&F signals, i.e. 1 PPS and 10 MHz, were delivered from UTC(AOS) via cascaded link Borowiec-Toruń (330 km) and Toruń-Piwnice (15 km). To make the comparison of both methods of synchronization possible, the observation began under local synchronization and shifted to remote synchronization, with each segment lasting about an hour.

The initial analysis carried out at JIVE shows that the fringe visibility phase noise is very similar for both synchronization schemes for all four baselines to the Toruń station, over time-scales ranging from two seconds to 45 minutes. This is an encouraging starting point for further experiments and investigations.

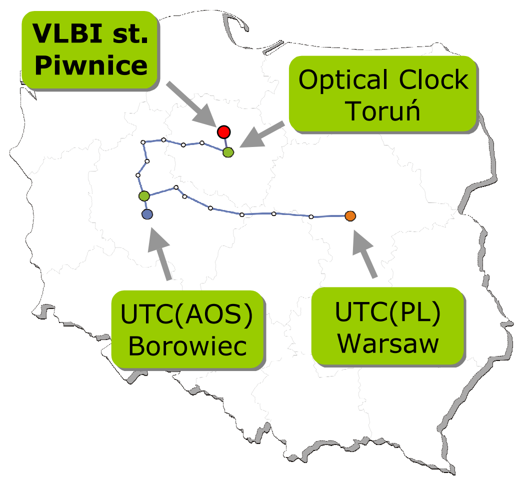


Fig. 1: Centre for Astronomy in Piwnice connected to the fiber optic T&F distribution network developed under OPTIME project.

# The optical $^{88}Sr$ lattice clocks and stabilized fibre links: a frequency reference for the VLBI system over 15.5 km link and an absolute measurement of the clock transition over 330 km link

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We report a system of two independent strontium optical lattice standards with $^{88}Sr$ probed with a single shared ultra-narrow laser [1,2]. We achieved frequency stability (frequency between two standards) of $7\times10^{-17}$.

The 15.5 km-long stabilized fibre optic link between KL FAMO and Toruń Centre for Astronomy made possible to use the optical clocks as a frequency reference for the 32 m precise parabolic antenna of the radio telescope in the Toruń Centre for Astronomy participating in the VLBI networks.

The absolute frequency of the clock transition can be measured by the use of an optical frequency comb referenced to the UTC(AOS) and UTC(PL) [3,4] via the 330 km-long distance stabilized fibre optic link of the OPTIME network [5].

We present current status of the KL FAMO optical lattice clocks, including their frequency stability, the uncertainty budget and the measured absolute frequency of the $^1S_0$-$^3P_0$ clock transition. The value of the absolute frequency of the clock transition was verified by series of measurements on two independent optical lattice clocks and agrees with recommendation of Bureau International des Poids et Mesures.

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# Elimination of Spurious Modes in Zinc Oxide Resonators

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In this paper a novel piezo-acoustic device, based on suspended piezoelectric micro-resonators is presented. The structure of this kind of resonator consists of metal interdigitated (IDTs) electrodes acoustically coupled within a Zinc Oxide (ZnO) thin film suspended on monocrystalline (100) silicon membranes. A detailed study has been realized on micro-resonators topology, in order to identify the optimum geometrical parameters (especially the length and the number of IDTs electrodes) affecting the micro-resonators performances.

We analyze several possibilities to increase the quality factor Q and the electromechanical coupling coefficient $k_t^2$ of the devices, for different finger numbers (N=25, 40, 50 and 80) and different lengths (L=25λ, 35λ, 42λ and 50λ) of inter-digitated (IDTs) electrodes. The measured extracted Q confirms that reducing the length and the number of IDTs fingers enables to reach better electrical performances at 700 MHz. Our measured results show that for an optimized micro-resonator device having a IDTs length of 25λ and 40 finger electrodes, we obtained a Q of 1180 and a $k_t^2$ of 7.4% which allowed achieving a very high figure of merit (FOM= $k_t^2.Q$) of 87 which is better by a factor of ~2 compared to similar micro-resonators recently proposed on lithium niobate [1] and on aluminum nitride [2].

Looking at [S] parameters of the measured circuit, we noted the presence of spurious modes in close proximity of the main mechanical resonance of certain micro-resonators: micro-resonators having a large number of IDTs electrodes have a plurality of resonance modes which are mixed together at the main mechanical resonance. By reducing the number of IDTs electrodes, resonance peaks are very selective because spurious modes are strongly attenuated especially for IDTs having N=40 which corresponds to the highest Q, and disappear completely when N = 25 IDTs. On the other hand, when N=25, the equivalent motional impedance $R_m$ increases and this is why the quality factor go down again.

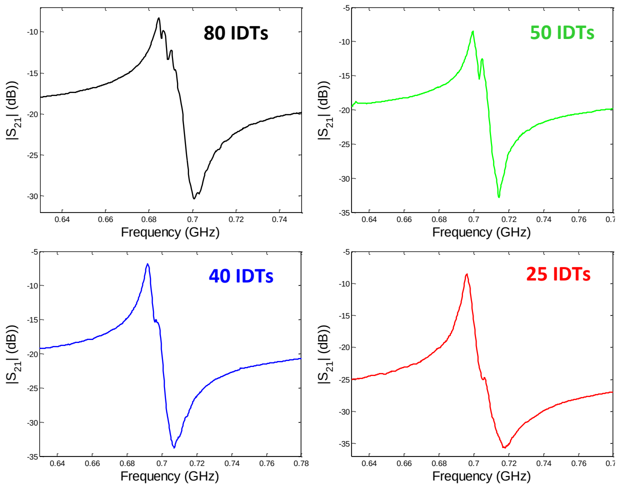


Fig. 1: Measured transmission response of fabricated ZnO micro-resonators operating at 700MHz with four different IDTs number

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# Searching for Dark Matter with Atomic Clocks and Laser Interferometry

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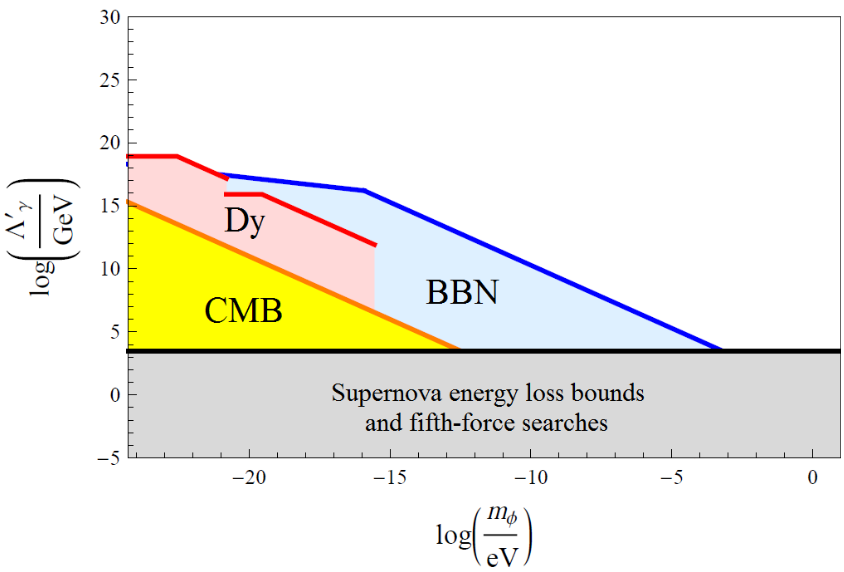
We propose new schemes for the direction detection of low-mass dark matter with atomic clock and laser interferometry experiments. Dark matter, which consists of low-mass bosons, can readily form an oscillating classical field that survives to reside in the observed galactic dark matter haloes if these particles are sufficiently light and weakly interacting.

We have recently shown that the interaction of an oscillating classical dark matter field φ with Standard Model fields via quadratic-in-φ couplings produces both a 'slow' cosmological evolution and oscillating variations in the fundamental constants [1]. Oscillating variations in the fundamental constants produce oscillating shifts in the transition frequencies of atomic clocks and other atomic systems, which can be used as high-precision probes to search for dark matter. Using the recent atomic dysprosium spectroscopy data of [2], we have derived limits on the quadratic interaction of φ with the photon that improve on existing constraints by up to 15 orders of magnitude [1] (see the red region in the figure shown). We have also proposed the use of laser and maser interferometry, in which a photon wavelength is compared with the interferometer arm length, as a novel high-precision platform to search for dark matter, with effects due to the variation of the electromagnetic fine-structure constant on alterations in the accumulated phase enhanced by up to 14 orders of magnitude [3].

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# Recent Advances in Compact Rubidium Frequency Standards at KRISS

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We report on recent advances in the laser-pumped Rb vapor cell clock based on a magnetron-type microwave cavity [1] at KRISS. The overall system size has been reduced by integrating the physics package with a customized microwave synthesizer, which represents the high short-term stability derived from a low noise compact OCXO. We summarize the systematic frequency shift observed in this system, and discuss possible improvements to the setup. The stability at the current stage marks $4x10^{-13}$ at 1 s and stays $10^{-13}$ level for integration time up to 10000 s in the presence of linear drift compensation.

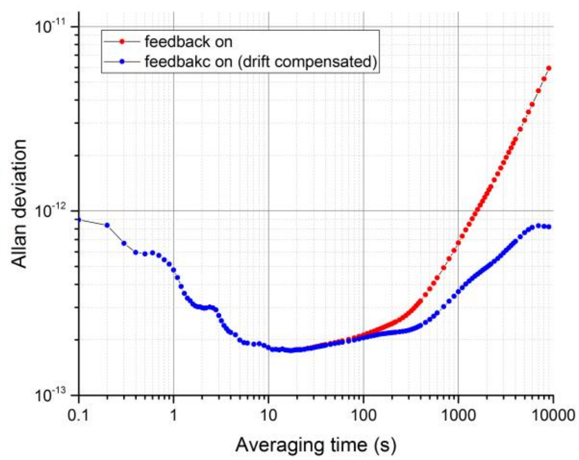


Fig. 1: Allan deviation obtained using a high resolution counter (Microsemi 5125A test set) for the oscillator stabilized to Rb clock transition (red). Also shown is the result of linear drift compensation (blue).

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# Efficient carrier envelope offset frequency stabilization through gain modulation via stimulated emission


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A novel scheme for intra-cavity control of the carrier-envelope offset frequency ($f_{CEO}$) of a mode-locked Er:Yb:glass diode-pumped solid state laser based on the modulation of the laser gain via stimulated emission is demonstrated [1].

In the Er:Yb:glass system, energy transfer mechanisms from sensitizing $Yb^{3+}$ to $Er^{3+}$ ions introduces a few-kHz low pass filter in the pump power to laser cavity transfer function [2]. Here, the gain of the Er:Yb:glass medium is modulated directly by acting on the $Er^{3+}$ population inversion (*i.e.*, the effective gain of the fs-cavity) by means of stimulated emission from an auxiliary cw-laser emitting within the $Er^{3+}$ emission band, as shown in Fig. 1. In this way, the $Yb^{3+}$ to $Er^{3+}$ energy transfer induced low-pass filter is bypassed and the whole system transfer function is now described by a single second order low pass filter corresponding to the three-level-laser transfer function of the $Er^{3+}$ system. This allows to push the phase lock bandwidth up to a limit close to the relaxation oscillations frequency of the erbium system.

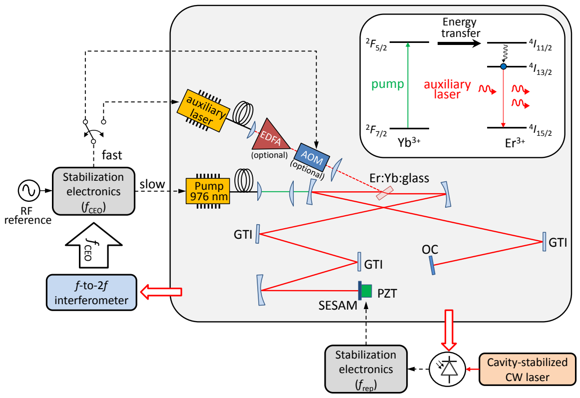


Fig. 1: Schematics of the 100 MHz repetition rate femtosecond cavity architecture including the auxiliary modulation laser. Inset: Energy diagram of the Er:Yb:glass system.

Fig. 2 shows the spectrum of the $f_{CEO}$ beatnote signal using the novel and the classic pump-only actuation approaches. A $f_{CEO}$ lock bandwidth above 70 kHz has been achieved with the fully stabilized system, more than a factor 2 higher than what is usually achieved with the traditional pump current modulation method [1], [3]. With the repetition rate of the laser stabilized to an optical reference (Fabry-Perot cavity stabilized cw-laser) via an intracavity piezo-electric transducer, $f_{CEO}$ integrated phase noise figures down to 120 mrad [1 Hz – 1 MHz] were obtained with this novel approach.

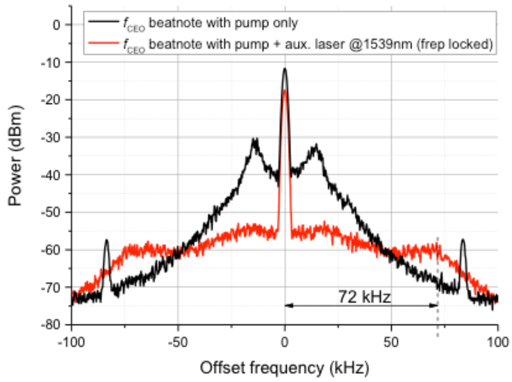


Fig. 2: Stabilized $f_{CEO}$ beatnote signal; Black curve: using only the pump power as an actuator. Red curve: using the pump power and the auxiliary laser as actuators, RBW=1.8 kHz, center frequency 342 MHz.

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# Interrogating optical clocks beyond the coherence limit of the clock laser

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The stability of optical atomic clocks is mainly limited by the ultrastable clock laser used for interrogation: In single ion systems; the quantum projection noise is set by finite interrogation times [1] while lattice clocks suffer from laser frequency noise via the Dick effect [2]. Even with the state of the art clock lasers [3] the interrogation time is limited by the coherence time of the laser. We will present a novel interrogation scheme that will allow building a compound clock using different species with probe times longer than the coherence time of the clock laser. The proposed technique utilizes a correlated interrogation sequence of two atomic clocks with one clock laser to resolve the phase ambiguity apparent in Ramsey interrogation beyond the coherence limit of the interrogation laser. Different to other correlated interrogation methods [4,5], it actually leads to an improved stability of the frequency delivered by the compound clock. In addition; the frequency ratio of the optical clocks used in this compound approach is arbitrary.

The scheme was tested using a single strontium optical lattice clock sequentially performing the interrogations that in a full implementation are done in parallel. We will discuss our results.

Acknowledgement:

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# Application of New Time Receivers in GLONASS

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One of the ways to improve GLONASS performance is to increase the accuracy of GLONASS Time generation and synchronization to Russian national time scale UTC(SU). This approach is planned to be realized by, first of all, increasing the accuracy of time scale comparisons between Central Synchronizers (Main and Reserved) which are the basis for GLONASS Time generation and State Time and Frequency Reference (STFR) which is the basis for UTC(SU) generation as well as by increasing the accuracy of mutual comparisons between the Main and Reserved Central Synchronizers [1].

Till recently, time scale comparisons between Central Synchronizers (CS) and STFR have been performed with using Reference Equipment (RE) at CS and TTS-3 receiver at STFR. RE was developed at RIRT in 2002 on the basis of 16-channel single-frequency receiver for Standard Precision (SP) GLONASS/GPS signals in L1 frequency band. TTS-3 receiver performs Standard Precision (SP) measurements in L1 frequency band and Precise (P) measurements in L1/L2 frequency bands. This equipment has provided the following accuracy:

– the error of calculating Main CS–STFR time scales offset about 8.0 ns (rms) by GLONASS signals and 3.0 ns (rms) by GPS signals;

– the error of calculating Reserved CS–STFR time scales offset about 13.0 ns (rms) by GLONASS signals and 10.0 ns (rms) by GPS signals;

– the error of calculating Main CS–Reserved CS time scales offset about 12.0 ns (rms) by GLONASS signals and 10.0 ns (rms) by GPS signals.

At the end of 2014 new equipment for time scale comparisons was additionally installed at CS and STFR: Time Transfer Unit TTU-1 developed at RIRT on the basis of 36-channel GLONASS/GPS receiver for SP signals in L1/L2 frequency bands – at the Main CS and a new GTR-51 time receiver for SP and P signals in L1/L2 frequency bands – at STFR.

In 2015 the new equipment at CS and STFR was tested and the following accuracy results were obtained:

– the error of calculating Main CS–STFR time scales offset with using single-frequency measurements in L1 band about 1.0 ns (rms) by GLONASS signals and 0.5 ns (rms) by GPS signals;

– the error of calculating Reserved CS–STFR time scales offset with using dual-frequency measurements in L1/L2 bands about 2.5 ns (rms) by GLONASS signals and 2.0 ns (rms) by GPS signals;

– the error of calculating Main CS–Reserved CS time scales offset with using dual-frequency measurements in L1/L2 bands about 2.5 ns (rms) by both GLONASS and GPS signals.

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# High Precision Time Interval Measurement Based on Temperature Compensation

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Time is one of the basic physical quantities which can be measured with high accuracy, especially, the time interval measurement usually possesses accuracy within sub-nanosecond level. Such measurement techniques are widely used in atomic time, satellite navigation, space tracking and control, quantum physics and instruments, etc. It is difficult to perform time interval measurement directly in engineering since system clocks with very high accuracy are required. Hence, several indirect measurement techniques are developed, the most representative approaches are analog interpolation, vernier method and time to amplitude conversion, etc.

The analog interpolation method performs the time interval measurement after a time expanding considering that sometimes the open and close signal interval is very small (smaller than the time marker) and it is difficult to measure the time interval by counting the time markers under those circumstances. The principle of digital vernier method is similar to vernier calipers, it takes use of two quantities with very small differences, sum all the difference values which is smaller than quantization unit until the summed value is larger than the quantization unit, then the precise difference value can be obtained after taking some computation. Although the analog interpolation method and vernier method can measure the time interval accurately, their uses are limited because they are too complex to be implemented. Time to digital conversion (TDC) becomes the mainstream method in recent years. TDC could do the digital quantization measurements by use of the delay line, which has a simpler structure and higher accuracy, thus TDC has a big advantage in measuring time interval. However, there exists an error in this method due to the inherent temperature susceptibility of analogue elements and the time shift. Error model about temperature and measurement must be established to compensate the errors, and so, to reach high accuracy.

TDC method based on differential delay lines is proposed in this paper. Considering the stability of the delay units, the proposed method tends to perform high speed status acquisition and data processing on the delay units. In this way, one can measure a short interval of time in high precision. Based upon the fact that the accuracy of TDC method suffers great impact from the temperature fluctuations, this paper has studied the relations between the temperature fluctuations and the TDC measurement error, and a real-time temperature compensation TDC measurement model has been established. Based on this model, a real time temperature compensation TDC method for time interval measurement is proposed. The experimental results indicate that the standard deviation for the measurement reduced from 270ps to 60ps after the temperature compensation, the improvement of accuracy is up to 4 times and more, which is better than the mainstream method for the time interval measurement (e.g., the standard deviation of SR620 is about 100ps). Thus, the proposed method is good enough to be used in high precision time interval measurements.

# OPTIME – Final Release


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This document describes the final stage of OPTIME project – which developed a self-calibrating, high precision dissemination system for time and frequency reference signals based on optical fiber links and ELSTAB devices developed at AGH University.

Right now the OPTIME system is about 800 km long. It consists of 4 links. The first one connects two UTC laboratories in Poland – UTC(AOS) realized at Astrogeodynamic Observatory, Space Research Centre – Borowiec near Poznan, and UTC(PL) realized at Central Office of Measures (GUM) – Warsaw. The length of this link is 420 km. The second link connects the UTC(AOS) laboratory with National Laboratory of Atomic, Molecular and Optical Physics (KL FAMO) in Toruń. The length of this link is more than 330 km. The third one connects KL FAMO in Toruń and Toruń Centre for Astronomy of Nicolaus Copernicus University (CA UMK) in Piwnice and it reaches about 15 km. The fourth link, about 40 km long, connects UTC (PL) laboratory and Orange Polska network synchronization center in Anin (Warsaw). The topology of the OPTIME time and frequency dissemination network is shown on Fig. 1.

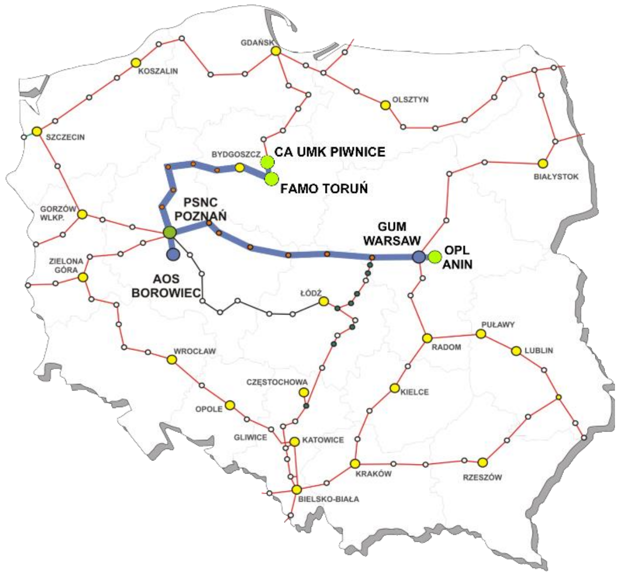

Fig. 1: Topology of OPTIME network in Poland

Moreover, this document describes a local time and frequency repository located in Poznan Supercomputing and Networking Center (PSNC), as well as monitoring and control system which allows to manage OPTIME network.

The document provides information about results of comparisons for the link UTC(PL) - UTC(AOS), and also for the link of AOS - KL FAMO laboratories, where two strontium optical lattice standards were build. Acknowledgement: Project OPTIME (no. PBS1/A3/13/2012) was co-founded by The National Centre for Research and Development – Poland. Strontium optical lattice standards were built by National Laboratory of Atomic, Molecular and Optical Physics (KL FAMO).

# First accuracy evaluation of the METAS-FoCS2 primary frequency standard

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The continuous primary frequency standard FoCS-2 is unique compared to all the other atomic fountain clocks which are operating in pulsed mode [1]. This approach makes use of the continuous beam of laser-cooled cesium atoms to circumvent limitations such as the Dick [2] effect and a large collisional shift at high atomic flux. Moreover, it contributes to the metrological diversity since the relative importance of the error budget contributors is different for the two types of fountains. In [3], we reported the evaluation of three frequency shifts specific to the continuous fountain: the light shift, the Zeeman shift and the end-to-end cavity phase shift below the $10^{-15}$ level.

Until recently, however, FoCS-2 was still limited by an unknown effect which limited the frequency accuracy at a level of $1.5{\cdot}10^{-13}$, by producing a change in the clock frequency when the velocity of the atoms was changed. In-depth analysis [4] pointed out the presence of spurious surface currents propagating along the coaxial cables, and generating unwanted microwave fields in the atomic free evolution zone.

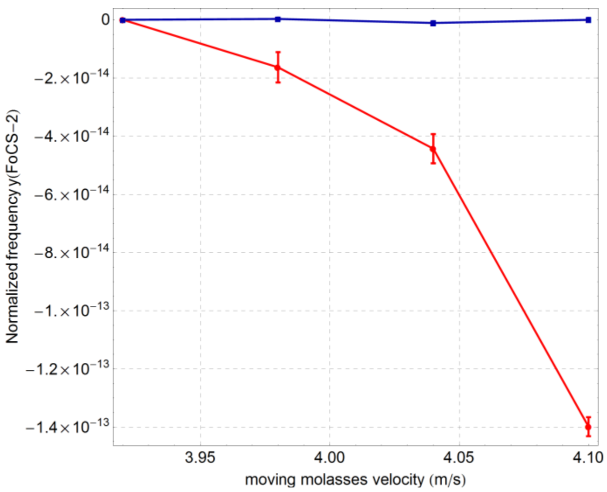


Fig. 1: Normalized frequency offset of FoCS-2 shown as a function of the atomic launch velocity. Red dots (blue squares) show the measurements before (resp. after) the installation of the graphite cylinder.

We show that this effect was fully eliminated after installation of a graphite cylinder on the top of the microwave cavity in Fig.1. This structure strongly absorbs any residual microwave field and thus protects the free propagating atoms from any perturbation. This result paves the road to the full metrological evaluation of FoCS-2.

Residual microwave leakages have been evaluated using different techniques and have proved to be consistent with an uncertainty budget for FoCS-2 below the $10^{-15}$ level. The experimental validation of the theoretical predictions for the cold-collision shifts at optimal flux was successfully achieved and has showed no significant frequency shift at the $10^{-15}$ level. The first results of the evaluation of the microwave cavity-related frequency shifts will be shown.

Finally, a first complete uncertainty budget for FoCS-2 will be presented and the future optimization of the fountain will be discussed.

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# Carrier-envelope offset characterization in a semiconductor modelocked laser without *f*-to-2*f* interferometry

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Phase-stabilization of the carrier-envelope offset (CEO) frequency $f_{CEO}$ is required in many frequency comb applications. The standard approach using *f*-to-2*f* interferometry for CEO beat detection is very demanding in terms of laser parameters. This makes it especially challenging for some novel frequency comb technologies, such as semiconductor modelocked lasers, due to the difficulty to generate the required coherent octave-spanning supercontinuum spectrum. For such lasers, a preliminary characterization of the CEO noise level would be an important first step towards a future phase-stabilization. Relevant parameters include an estimation of the required feedback bandwidth to achieve a tight phase lock and the $f_{CEO}$ modulation response.

For this purpose, we recently developed a novel experimental scheme to characterize the CEO frequency without directly detecting it, using an appropriate combination of signals obtained from the comb and a reference continuous-wave laser [1]. Using this method, both the noise spectrum and the modulation response of $f_{CEO}$ of an Er:fiber comb were thoroughly characterized for proof-of-principle validation (Fig. 1a). In the present submission, we will first review this CEO characterization method, and then present its implementation with a modelocked vertical external-cavity surface-emitting laser (VECSEL). The CEO beat of a VECSEL was recently detected for the first time after external amplification and pulse compression [2], but the beat signal was not suitable for noise analysis and was likely affected by extra noise induced in the amplification process. With our novel method, we characterized for the first time the noise properties and the modulation response of the free-running CEO frequency in a semiconductor modelocked laser. A required feedback bandwidth of ≈300 kHz is estimated from the measured CEO frequency noise spectrum (Fig. 1b), which appears to be within reach of the assessed $f_{CEO}$ transfer function for pump current modulation. This work paves the way to the first CEO-stabilization of a modelocked semiconductor laser.

In addition, we also investigated the absolute frequency fluctuations of the free-running $f_{CEO}$ that showed a high correlation with the relative variation of the laser output power (Fig. 1c).

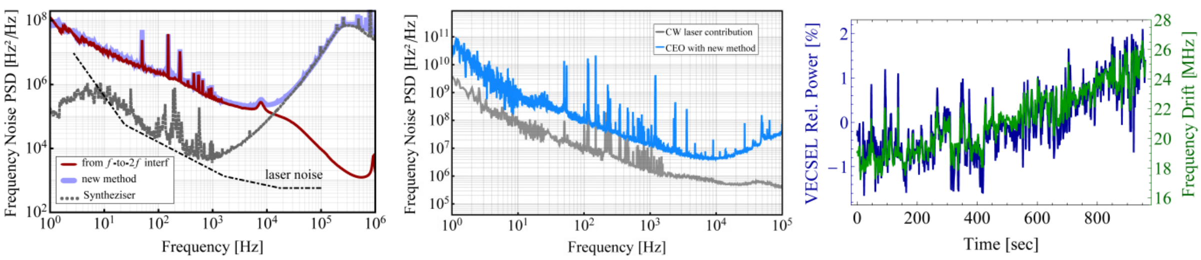


Fig. 1: (a) Proof-of-principle validation of the proposed CEO characterization method of an Er:fiber comb. An excellent agreement is obtained between the CEO noise measured with the new method (blue) and assessed using standard *f*-to-2*f* interferometry (red). (b) Assessed CEO noise of a modelocked VECSEL with 1.8 GHz repetition rate. (c) Measured CEO frequency drift and correlation with the laser output power.

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# Precision Test of the ac-Stark Shift in a Vapor-Phase System

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The ac-Stark shift (also known as the "light shift") is one of the most important physical processes that arises in atom-field interactions, from both a basic and applied point of view. In the field of frequency standards, for instance, the ac-Stark shift affects the 0-0 hyperfine transition in optically-pumped alkali-metal vapors, in particular in vapor-cell Rb atomic clocks. Indeed, light-shift induced jumps in the frequency of on-orbit Rb atomic clocks have been observed, displaying a fractional frequency magnitude as large as ~ $10^{-13}$.

In this work, we present a new methodology for measuring the ac-Stark shift in a Rb cell with a high level of accuracy. Specifically, we take advantage of the pulsed optical pumping technique and of the Ramsey interaction scheme to perform frequency measurements with a resolution of~ $10^{-15}$ [1]. After preparing the Rb atoms with a strong laser pulse, the atoms experience two consecutive microwave pulses according to the Ramsey scheme. During the free evolution, a low power perturbing laser pulse tuned to the D1 absorption resonance is applied to the atoms. In this way we were able to verify the AC Stark shift theory for a perturbing laser tuned over a broad optical frequency range (18 GHz). We point out that different from experiments done in the past, in our case the optical pumping light and the ac-Stark shift perturbing field are not the same, and are not applied simultaneously. In this way, we were able to measure the ac-Stark shift very clearly, with negligible systematic optical pumping effects. Over the full frequency range the agreement between semiclassical theory [2] and experiment is very good (better than $5\times10^{-2}$), and in our experiments we test both the frequency dependence of the scalar and, for the first time, tensor components of the light shift [3].

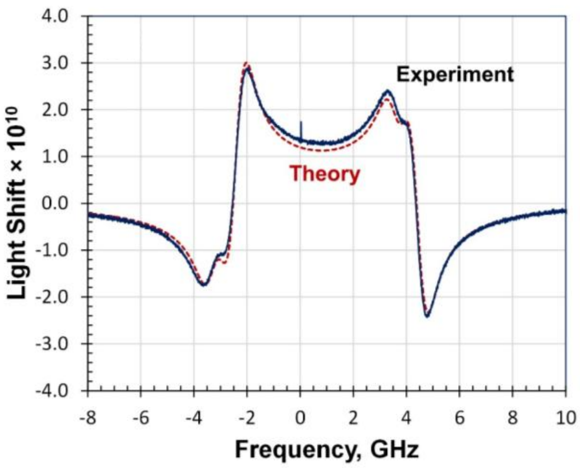


Fig. 1: Comparison of the measured ac-Stark shift at a resonance cell temperature of 40 °C with theory; the perturbation laser is only on during the Ramsey period of the pulse sequence.

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# Study of the Misalignment between Electromagnetic Fields Interacting with Rb Atoms in a Cavity with Losses

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For the realization of high-performance Rb vapor cell clocks a good cavity design is required to provide a well–defined microwave magnetic field that will ideally couple only to the desired atomic clock π-transition (e.g. the $| F=1, m_F=0\rangle \leftrightarrow |F=2, mF=0\rangle$ transition in the $5S_{1/2}$ ground state of $^{87}$Rb, at $\nu_{Rb} \approx 6.835$ GHz). In a practical clock implementation however, the electromagnetic fields interacting with the atoms may be slightly misaligned with respect to the required quantization axis and thus may degrade the clock performance by increasing the coupling to the unwanted σ– and σ+ transitions. In this study we investigate the impact of misalignment of the static and/or microwave magnetic fields from the laser propagation direction and quantify its effect via the cavity Field Orientation Factor (FOF) that can be further linked to the stability of the clock.
The microwave magnetic field amplitudes driving the resonance transitions are calculated for the case of the cylindrical geometry with the static magnetic C-field misaligned to the central axis of the cavity. In the clock, the optical signal detected depends on the amplitude of the field driving the corresponding transition. The 2D field image profiles related to the detected signal are obtained by numerical integration along the direction of the optical beam (fig. 1). The misalignment results in a significant increase of the field driving the unwanted σ– and σ+ transitions, especially in the center of the cavity.

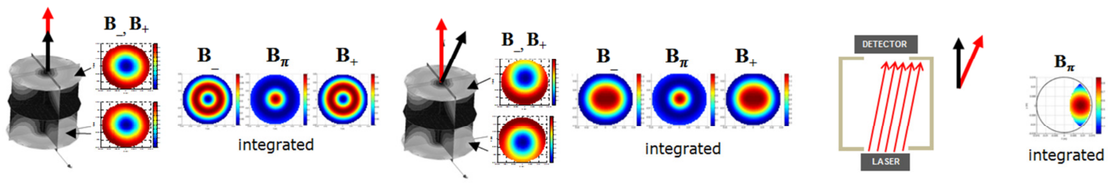


Fig. 1 Ex. of field misalignment in a circular cavity. The directions of the C-field and the laser light are represented by the red and black arrows. The fields are shown for cut planes (x-y) as well as the obtained by the detector - integrated along the direction of the light beam.

In the more realistic case of cavity with losses, the phase difference between the transverse components of the magnetic field in the cavity breaks the azimuthal symmetry for the driving B– and B+, and when combined to both misaligned C-field and optical field results in different coupling for σ– and σ+. Our analysis is suitable to reveal how the geometry of the cavity influences the resonance transitions in a realistic implementation of the physics package and is relevant in line with newly developed cavity characterization techniques based on field imaging [1, 2]

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# Rb-stabilized optical frequency reference at 1572 nm

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The integrated-path differential-absorption lidar (IPDA) technique allows high-precision remote sensing of the atmospheric $CO_2$ concentration. Such a lidar instrument is based on a laser source emitting pulsed radiation at a precise wavelength corresponding to an appropriate $CO_2$ absorption line in the near-infrared. To provide a global and denser distributed set of measurements allowing the identification of sources and sinks of CO2, a satellite mission is envisaged.

For this purpose, we have developed a compact frequency reference laser system in the 1.5-µm spectral region [1] (Fig. 1). A 1560-nm distributed feedback (DFB) laser with ~1-MHz linewidth acts as a master laser source. It is frequency-doubled in a PPLN waveguide and stabilized onto a rubidium transition at 780 nm using a compact sub-Doppler absorption scheme in a 2-cm long vapor glass cell [2]. Part of the stabilized 1560-nm light feeds an optical frequency comb (OFC) generator, which consists of a waveguide electro-optic modulator (EOM) enclosed in a Fabry-Perot cavity. The generated OFC covers the spectral interval between 1540 nm and 1580 nm, with a line spacing of 10 GHz corresponding to the EOM driving frequency. A slave DFB laser is finally offset-locked to a line of the OFC. The comb line, the EOM driving frequency and the offset frequency are chosen so that the slave laser emits at the desired wavelength of 1572.02 nm for the $CO_2$ lidar system.

A relative frequency stability of the master laser of $5.2 \cdot 10^{-12}$ at 1 s integration time has been demonstrated. At 1572 nm, a relative frequency stability of $1 \cdot 10^{-11}$ at 1 s has been obtained, reaching $< 4 \cdot 10^{-12}$ from 3,000 s up to at least 3 days. The system accuracy is mainly limited by the frequency precision of the master laser. For the direct $^{87}$Rb F2→F'3 transition, a frequency accuracy lower than 100 kHz and a reproducibility of ~20 kHz have been reached. A study of the amplitude and frequency noise of the setup, in particular for the frequency doubling unit, is currently conducted and will be presented for the frequency doubling unit.

This work is supported by the Swiss National Science Foundation (project number 156621).

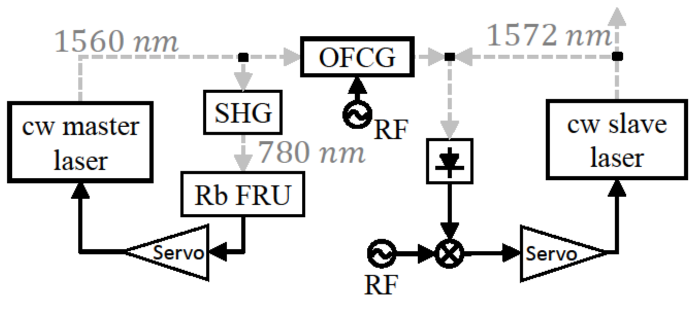


Fig. 1: Schematics of the laser system. Dashed grey lines correspond to optical fiber links, black lines correspond to electrical links. SHG: second harmonic generator; Rb FRU: rubidium frequency reference unit; OFCG: optical frequency comb generator; RF: radio-frequency oscillator.

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# Network Time Security specification: protecting network-based time synchronization

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Time synchronization protocols play an increasingly important role in packet switched networks. Areas of applications include distributed and internet-connected production chains, and the finance industry, especially high-frequency trading. Many national metrology institutes apply the Network Time Protocol (NTP) – one of the predominant time synchronization protocols – for the dissemination of UTC. In many use cases, the protection of time synchronization protocol is indispensable, either because of existing threats or because of compliance or legal reasons. Neither NTP nor the Precision Time Protocol (PTP) are able to protect time synchronization packets in modern and complex networks adequately. Although NTP provides two security procedures for the protection of integrity and authenticity, neither of them fulfills state-of-the-art security requirements. The situation concerning PTP is similar: although the standard specifies a security procedure within Annex K, this annex is typically not implemented by the manufacturers.

In this paper, we present the Network Time Security specification (NTS). It comprises security measures that are designed to protect time synchronization messages. The security goals aspired to by the NTS specification are based on a profound threat analysis for time synchronization protocols performed by the Internet Engineering Task Force (IETF) and specified in RFC 7384 [1]. Apart from common security requirements, such as protection of integrity and authenticity, RFC 7384 also requires that applied security measures not impede the performance of the time synchronization. NTS meets these requirements by subdividing the synchronization protocol into two different phases: authentication with key exchange, and time exchange. The second phase is particularly sensitive to latencies introduced by cryptographic security operations. Thus, symmetric cryptography is applied to fulfill the security requirements during this phase. The first phase incorporates certificate-based authentication schemes in order to provide the scalability required and utilizes asymmetric cryptography to secure the key exchange.

NTS is specified within the NTP working group of the IETF. It is accompanied by a document that describes the application of NTS to NTP. IEEE's P1588 working group that is currently revising PTP is considering aspects of NTS for the protection of PTP.

The development of the NTS specification is assisted by formal security analysis of the modeled security protocol. This is done by means of model checking and theorem proving. This approach has proven to be very useful for finding security vulnerabilities during the process of protocol specification.

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# A highly tunable low-drift laser referenced to an atomic transition

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Stable lasers with a narrow linewidth are an important tool for precision spectroscopy. Here, we present a simple and versatile laser system for spectroscopy of trapped highly charged ions at sub-Kelvin temperatures. While covering a tunable wavelength range from 780 - 890 nm we reach a linewidth and absolute frequency fluctuations on the 50 kHz level, corresponding to a fractional instability below $1 \times 10^{-10}$. Within 90 h of operation we measure a linear drift of $(0.28 \pm 0.30)$ kHz/h.

As frequency reference we use a low-cost 780 nm DFB-laser stabilized to a hyperfine transition of the rubidium D2 line by modulation transfer spectroscopy. The stability of this laser is transferred to the spectroscopy laser by use of an optical transfer cavity. Tunability over 800 MHz in closed-loop operation is possible by means of the offset sideband locking technique [1]. Possible systematic effects on the long-term stability, such as fluctuating temperature, magnetic field and laser power are carefully suppressed or calibrated. We measure the instability of both reference and spectroscopy laser against a Maser-stabilized frequency comb, and the respective linewidths against an ultra-stable laser. Our approach combines the long-term stability of a broad atomic transition with the linewidth narrowing capabilities of an optical cavity.

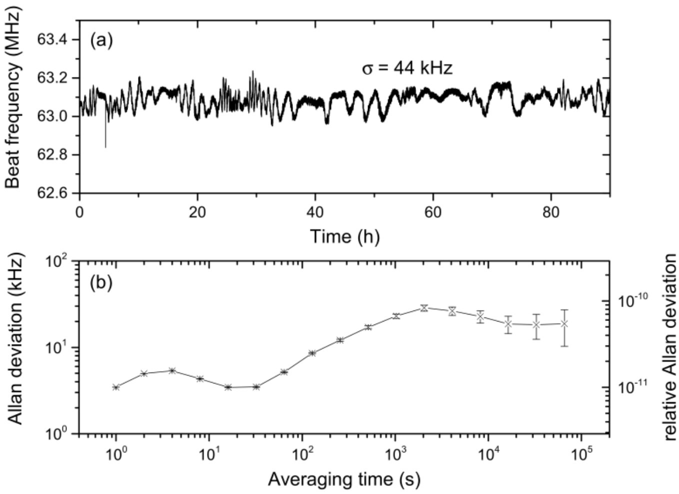


*Fig. 1: (a) Trace of the beat frequency between spectroscopy laser and frequency comb over time. (b) Corresponding Allan deviation of the transfer locked spectroscopy laser*

The laser system presented here will be used for spectroscopy of the $1s^2 2s^2 2p\,^2P_{1/2}$ - $^2P_{3/2}$ transition in trapped $Ar^{13+}$ ions at 441 nm. The transition frequency is known with an accuracy of 400 MHz. Sympathetically cooled in a laser cooled cloud of beryllium ions the 100 Hz natural linewidth is expected to be broadened to several 100 kHz [2].

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# New Approaches in Deep Laser Cooling of Magnesium Atoms for Quantum Metrology

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Laser cooling and trapping of atoms play crucial role in quantum metrology, which has been rapidly developing in recent years. One of the most essential directions in metrology concerns producing the new-generation frequency and time standards. These standards are based either on the large number of cold neutral atoms trapped in the optical lattice or on a single ion, trapped in the Paul trap. The former direction is much younger than the latter one, but it has already demonstrated the record values of frequency instability and inaccuracy $\sim 10^{-18}$ [1].

Magnesium atom has some advantages over the other candidates (Yb, Ca, Sr, Hg) for creating the optical-lattice frequency standard [2]. Unfortunately, deep laser cooling of magnesium atoms close to the recoil energy limit (several μK) is the intricate problem in contrast to the other elements. The minimum temperature of Mg atoms that has been obtained by laser cooling is about 500 μK [3]. Recent experimental results showed the temperature of magnesium cloud at the level of several μK (see [4] and references in it). However, velocity-selecting cooling technique was applied immediately after the magneto-optical-trap stage (MOT). It led to dramatic loss in number of cold atoms. At the same time, temperature of atoms in the MOT was about 1 mK. Therefore, we can state that the problem of deep cooling of magnesium atoms by means of laser radiation is still unsolved. Moreover, increasing ultracold atomic number has principal importance for many applications of cold atoms. For instance, frequency-standard stability increases with increasing number of atoms in the lattice.

In the present work we have developed two possible ways for overcoming the considered problem with magnesium atoms. One of them is to exploit 1D optical molasses composed of orthogonal linear polarizations of counterpropagating laser beams (for instance, it can be applied right after the MOT stage, which uses the strong dipole transition $^1S_0 \rightarrow {}^1P_1$). The second way implies using "non-standard" MOT with linear polarizations of beams, having 45-degrees mutual angle. All our conclusions are based on the detailed theoretical study for the triplet dipole transition $^3P_2 \rightarrow {}^3D_3$ ($\lambda$=383.8 nm). Two approaches have been used for studying quantum kinetics of cold atoms: widely used semiclassical approximation as well as quantum treatment with full account for the recoil effect. The optimal parameters of electromagnetic fields have been calculated for reaching the lowest temperatures and large atomic numbers.

The work of D.V. Brazhnikov, A.E. Bonert, A.N. Goncharov and A.V. Taichenachev was supported by the Russian Science Foundation (proj. 16-12-00054). O.N. Prudnikov and V.I. Yudin were supported by the RF Ministry of Education and Science (order 2014/139, proj. 825), by grants of the RFBR (14-02-00806, 14-02-00712) and by Presidium of the SB RAS.

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# Optical Two-Way Time Transfer with Picoseconds Accuracy over Telecommunication Fiber

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We have developed a new Two-Way Time Transfer (TWTT) system implementing standard optical telecommunications Small Form-factor Pluggable (SFP) transceivers to transfer timing information between two or more terminals with the accuracy of the order of 1 ps via optical fibers of the length up to several tens of kilometers. The heart of the measurement technique is an event timing device using a surface acoustic wave filter as a time interpolator, which allows registration of the times-of-arrival of pulses with sub-picosecond timing resolution, linearity and stability [2]. These pulses are derived from the optical signal which is used for communication between the terminals.

In the past, a lot of effort went into the development of a very precise TWTT using a coaxial cable as the transmission link [1] with the aim to identify unaccounted system delays at the Geodetic Observatory Wettzell. The main disadvantage of this approach is a rather steep increase of the time transfer error with the length of the link. It provides very good results for links of the length up to several hundreds meters, but on distances longer than several kilometers cannot be expected accuracy better than 100 ps. This disadvantage can be resolved by using the optical telecommunications technology.

The TWTT technique perfectly eliminates influence of the large link delay, but it does not suppress impact of some partial internal delays within the terminals. These internal delays are relatively small, but not negligible, and their dependence on temperature and level of the received optical signal can be a source of an unpleasant systematic error and instability in the time transfer. Thus the key goal of the design of a very precise optical TWTT system is keeping these systematic errors as low as possible.

Therefore we performed a series of experiments focused on the TWTT instability caused by the internal delays in the terminals. We investigated two different configurations of the optical TWTT terminals with the feedback coupling of the transmitted signal in optical and electrical domain. The achieved results have been used for the optimal design of the time transfer system. The operational tests of this optical TWTT system confirmed the accuracy of the time transfer on the picosecond level, very good temperature stability and insensitivity to the optical power level.

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# An Yb Optical Lattice Clock at KRISS: Current Status

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In this paper, we report the current status of an Yb optical lattice clock at Korea Research Institute of Standards and Science (KRISS), Korea.

Our Yb clock system has been moved to a new building with better environmental conditions in terms of stable temperature and humidity, reduced vibrational noise etc. During the moving process, we made several improvements and recently we observed again the clock transition spectrum as shown in Fig. 1.

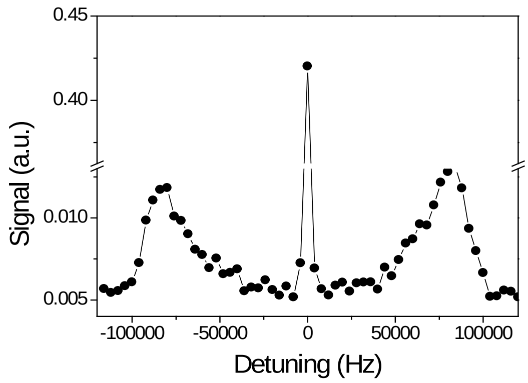


Fig. 1: Clock transition spectrum with red and blue sidebands.

Currently, the total uncertainty is mainly dominated by the shifts due to the lattice laser and blackbody radiation.

We are making efforts to evaluate the lattice laser induced shifts (electric dipole, magnetic dipole, electric quadrupole, and hyper-polarizability) with uncertainty at or below $10^{-18}$ level. We are developing a build-up cavity to enhance the optical lattice depth as shown in Fig. 2. The finesse of the cavity is about 155 and trap depth of up to 2000 recoil energy is expected to be reached. The results will be presented at the forum.

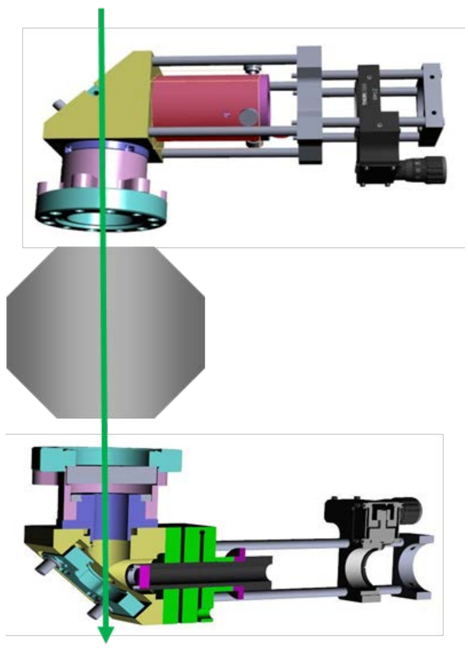

Fig. 2: Build-up cavity for enhanced lattice depth. Trap depth of up to 2000 recoil energy is expected to be reached.

To reduce another dominant shift, blackbody radiation (BBR) shift, we are developing a thermal shield with minimized temperature distribution since the uncertainty mostly comes from the uncertainty of the surrounding temperature. The results will also be presented in more detail in another presentation from KRISS.

# Optical Two-Way Timing System for Space Geodesy Applications

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Until now time itself is not an observable in space geodesy. The major reason for this fact is the considerable difficulty to keep track of the phase of the clock oscillation between the point of origin and the point of the measurement. However, if geodesy will attempt to provide a reference frame fully based on general relativity, a proper treatment of time is mandatory.
The Geodetic Observatory Wettzell is currently in the process to modernize the timing system such that the phase of the master clock can be established at all times. The ultrashort pulses of an optical frequency comb are transporting both time and frequency from the master clock of the observatory to the individual space geodetic techniques, namely Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Navigation Satellite System (GNSS), using a two-way approach, which is in the literature known as the Einstein Synchronization [1].
In order to verify the functionality of this system not only in sense of delay stability but also accuracy, we have developed a new TWTT system based on the exchange of timing codes via standard optical telecommunications Small Form-factor Pluggable (SFP) transceivers to transfer timing information between two or more terminals with the accuracy of the order of 1 ps via optical fibers of a length of up to several tens of kilometers. The heart of the measurement device is an event timing module using surface acoustic wave filters as a time interpolator, which allows the registration of the times-of-arrival of electrical pulses with sub-picosecond timing resolution, linearity and stability [2]. These pulses are derived from the optical signal, which is used for the communication between the terminals. Great care was taken in order to minimize terminal internal delays instability, which can be the result of temperature changes inside terminals. The design, applications and the first experiments at GO Wettzell will be discussed.

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# Verification of Time Signals

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A continuous broadcast transmission of time information is actually common. In every data network the current system time has to be available in any devices. Most time signals are transmitted via continuous simplex terrestrial broadcast radio links, like DCF77 in Germany, MSF in the UK, JJY40/60 in Japan and WWVB, WWV and WWVH in USA.

Such a continuous time signal data stream can also be generated or manipulated by "man-in-the-middle" attacks. It is possible to manipulate the internal clock of individual devices depending on the location of the attacker. By manipulating the receiver's system clock, the control behavior of the device can be changed. The security mechanisms digital signatures and encryption doesn´t protect against man-in-the-middle attacks, for example by delaying the time signals using a replay attack.

Possible attack scenarios on broadcast data services have been published [1].

Because of a manipulated System time, controlled devices in a network can be damaged or destroyed, e.g. Wind turbines or generators in a smart grid.

This paper describes a method to verify received time signals for different existing time transmission systems. By this approach, the time between two time signals is continuously measured and compared with the time difference calculated by the time information contained in the time signals. In other words, physical and logical information is compared. The physical time difference is directly calculated using the carrier frequency of the transmission system (for example: DCF77 transmission system uses a carrier frequency of 77.5 kHz with ASK modulation). A time counter is clocked by the received carrier frequency of the system. The physical time difference between the transmission of two time signals can be derived by the number of oscillations. The logical time difference is given by the content of the time signals. Figure 1 shows an example of transmission. It shows the received time signals ($ts_1$-$ts_5$) with the contained time information and the corresponding counter values ($tc_2$, $tc_4$ and $tc_5$).

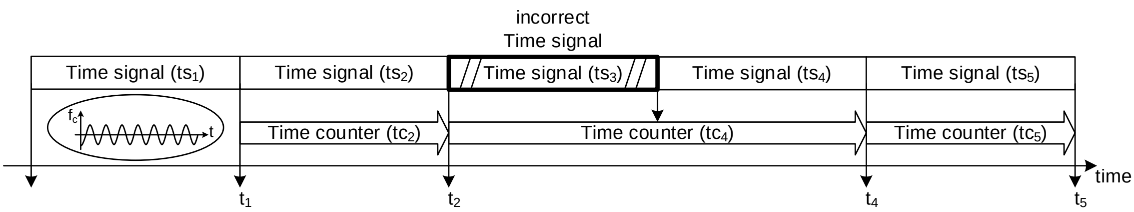


Fig. 1: Transmission of time signals with and without error

The time counter value (tc) is stored, evaluated, reset and compared with the logical time difference after any correct received time signal. The comparison of physical and logical time differences is continuously verified to detect time jumps, which may appear during the transmission of time signals. Manipulated or delayed time signals can accurately be identified. This method can be applied without changing the time distribution protocol and can applied to other time distribution services.

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# Research of Cesium Atom Clock Beam Intensity Associated with Collimator Structure

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Beam intensity of cesium atom emanated from collimator directly affected performance of cesium atom clock. This thesis analysed the process of cesium atom emanated from collimator, for cesium atom average mean free path matched collimator tube length in cesium oven working temperature, the thesis stressed reflection of the atom from the walls of the collimator tube[1]. Thesis proposed three assumptions in theory analysis, first assumption was that Knudsen type flow over at least a limited region was valid for caese in which a beam of useful directivity was formed. The second assumption was that in the limited region of Knudsen flow the density of atoms in the tube, atom density was related to the distance into the tube. The third assumption was that atoms leave each surface element with an angular distribution proportional to the cosine of the angle with the normal to the surface.

We attained expressions of atom peak intensity and beam width from theory analysis; Monte Carlo simulative calculation and experiment were adopted to prove theoretical expressions afterwards. In our experimental condition, the results were reasonable. We designed several multi-capilary collimators with hexagonal, circular, triangular and trapezoidal cross section in honeycomb structure. From the analysis results of atom peak intensity and beam width, we chose the preferable structure and dimension of collimator to improve cesium atom beam intensity and short term stability of cesium atom clock.

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# WR-ZEN: Ultra-accurate synchronization SoC based on Zynq technology

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Nowadays, most industrial synchronization systems rely on the Precise Time Protocol (PTP or IEEE1588) that provides sub-microsecond precision time transfer. However, there are some applications such as telecommunications or scientific infrastructures that have stricter timing requirements that must guarantee the timing service regardless of traffic load conditions. Recently, the White-Rabbit [1] (WR) technology has been proposed as alternative to provide deterministic sub-nanosecond synchronization using Gigabit Ethernet standard. It allows to transmit and receive regular data and timing information to/from the network over the same link in a reliable way. Currently, most WR nodes are implemented using only FPGAs and they can be plugged in a conventional computer or can be used as standalone node. Nevertheless, this approach presents some limitations because all the functionality must be implemented in the FPGA due to the lack of a hard microprocessor on the board.

The White-Rabbit Zynq Embedded Node [2] (WR-ZEN) is a platform based on the Xilinx Zynq SoC technology that solves these issues. It has a Processing System (PS) based on a dual core ARM hard processor that can run any conventional OS like Linux and simultaneously use the Programmable Logic (PL) inside the same chip. This design overcome the described node limitations and provides an embedded timing node with "PC-like" features. We have developed new capacities including warm updates, improved short-term clock stability, redundancy mechanisms or support of different FMC cards. The flexibility of the platform has motivated that WR-ZEN is under study to be used in important scientific infrastructures such as Square Kilometer Array (SKA) and Cherenkov Telescope Array (CTA) among others. In this contribution, we deal with the new platform design including hardware, gateware and firmware architecture (see Fig. 1). We describe the new clocking scheme, aspects of the Linux customization, kernel modules, user-space tools and the Fine Delay FMC support, clearly stating the benefits of the presented approach compared with previous WR platforms. Finally, we present experimental results and validation of the timing features compared with other solutions.

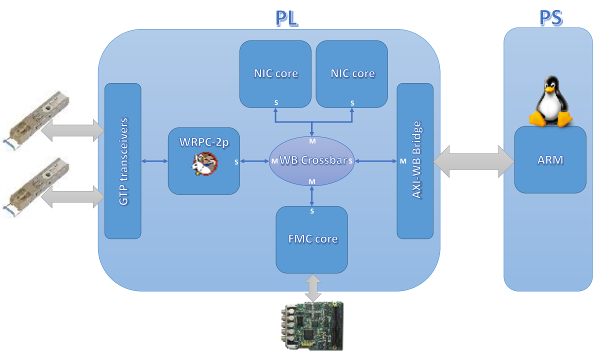


Fig. 1: WR-ZEN gateware architecture. The main core of the PL is the WR PTP dual port core (WRPC-2p) that implements the WR protocol. Other relevant cores included in the design are an AXI-WB bridge core to communicate with PS, NIC cores to manage the optical ports as standard network interfaces from Linux and a customized FMC core.

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# Dual Frequency Spin-Polarized Pumping


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Low-cost, low-consumption and high performance chip-scale atomic magnetometers and gyroscopes can find widespread applications. Low manufacturing cost is inherent to wafer scale MEMS fabrication technique used for a key element, a cell filled with noble gas and alkali metal atoms. For operation of the device, the noble gas atoms have to be polarized in spin-exchange collisions with alkali atoms, which are under optical pumping with the circularly polarized light. Efficient and stable spin-exchange optical pumping with a narrow linewidth laser is vital for achieving high performance figures. Here, we report on the effects of optical frequency detuning from the absorption resonance and propose novel approach to reduce such sensitivity.

Our optical test setup utilizes a DFB laser as a narrowband optical source and operate with 45° crossed circularly polarized pump and probe beams. Three-axis Helmholtz coil system provides a steady holding field in the pump beam direction and a second alternating magnetic field to drive the coherent spin precession in the orthogonal plane. We use Rb vapor cell with natural isotopic abundance of Rb and containing several hundred torrs of Xe and $N_2$ buffer, heated to 110°C. The hyperfine features in the absorption line are strongly collision broadened and overlap (Fig 1, red curve). Once on resonance, one would expect no large sensitivity to small variations in laser optical frequency. Fixing the frequency of coherent magnetic field (120 kHz in Fig 2, red curve) and scanning the amplitude of the holding field, we recorded the electron spin resonance (ESR) curve for the two Rb isotopes in the cell. Under single frequency (SF) interrogation, ESR curve reveals bias. Fixing then both the frequency of coherent magnetic field and the amplitude of the holding field, we measured the impact of the laser frequency detuning on the amplitude of ESR (Fig.3). Surprisingly, despite smooth profile of the absorption spectrum in Fig 1, hyperfine ground state lines in Rb reappear in the ESR spectrum (Fig 3, red curve shows example for $^{85}$Rb isotope). These features indicate that the laser frequency stabilization with MHz precision is required.

We find what we believe a pioneering solution enabling us to avoid such tight stabilization of the laser frequency. It consists in modulating the laser drive current so as to produce a two sidebands in the optical spectrum on resonance with the two hyperfine absorption lines in Rb. Dual frequency (DF) pumping and interrogation scheme flattens the ESR spectrum, reducing sensitivity to the carrier frequency detuning (Fig 3, blue curve). It also slightly reduces the bias and the width of ESR resonances (Fig 2, blue curve). These findings are important for miniature atomic sensors utilizing spin-polarized optical pumping.

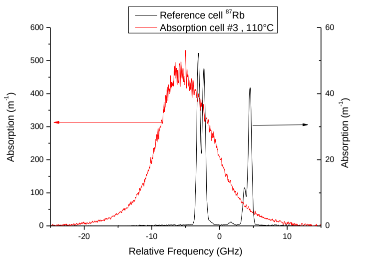


Fig. 1. Left: Measured absorption spectra of representative Rb-Xe-$N_2$ cell at 110°C (red curve) and of the reference cell with $^{87}$Rb and no buffer (black curve).

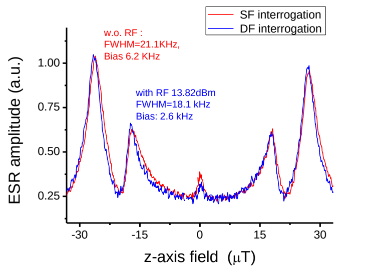


Fig. 2: ESR amplitude vs holding field in a cell with natural abundance Rb. Coherent magnetic field oscillates at 120 kHz. Data are taken under SF (red curve) and DF (blue curve) interrogation.

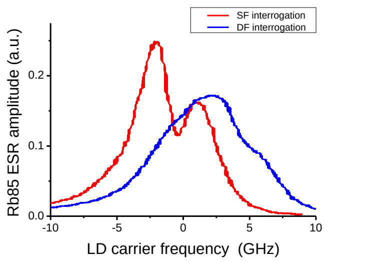


Fig. 3: ESR in $^{85}$Rb atoms at 145 kHz ($B_z$=31μT) vs carrier optical frequency under SF (red curve) and DF (blue curve) interrogation.

# An EOM with ultra-low residual amplitude modulation

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Electro-optic modulator (EOM) is the key component in many applications such as cavity-stabilized ultra-stable lasers. However, residual amplitude modulation (RAM) occurs when laser's phase is modulated by an EOM. RAM is caused by many effects, such as parasitic etalon effect between two parallel surfaces of EOM [1] and birefringence of the EOM [2]. Complex feedback controls have been applied to reduce RAM [2-3].

An EOM aiming at solving two mentioned problems without active control is shown in Fig. 1. It avoids parasitic etalon effects of the EOM. On the other hand, incident light with perpendicular polarizations is spatially separated, and incidence and emergence with Brewster's angle reflect part of laser with unwanted polarization state. Both additional polarizer and anti-reflective coating are not required any more.

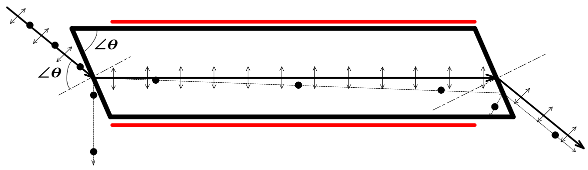


Fig. 1: Schematic of the home-made EOM. $\angle\theta$ is Brewster's angle, solid lines and dashed lines represent two perpendicular polarizations. Red lines represent electrodes.

We evaluate the performance of such an EOM by setting it into a standard PDH frequency-stabilization system, and compare with that of a commercial EOM (New Focus-4003) with a high extinction ratio ($>10^4$) polarizer in front to minimize RAM. Under same measurement conditions, RAM of the home-made EOM is lower than that of the other. Both systems` error signals (for PDH locking), directly corresponding to a frequency instability introducing by system noise, are shown in Fig. 2. It's clear that the setup using the home-made EOM is more stable than the other, and its Allen deviation is one order in magnitude lower at 1s.

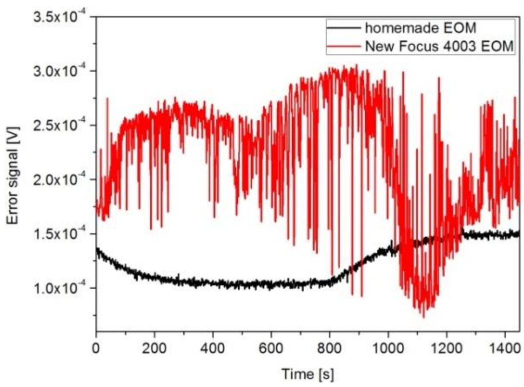


Fig. 2: Error signal of the setup with a New Focus-4003 EOM (red) and the homemade EOM (black).

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# Transferring frequency stability simultaneously to multiple wavelengths with an optical frequency comb

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Many applications, such as atomic clocks and long distance optical fibre links will benefit from a local oscillator with improved frequency stability [1]. Here we report using an optical frequency comb to simultaneously transfer the stability of a 1064 nm ultra-stable optical cavity to 4 independent optical atomic clock-relevant wavelengths ranging from 674 nm to 934 nm, a telecom laser at 1542 nm and a microwave signal at 9.2 GHz.

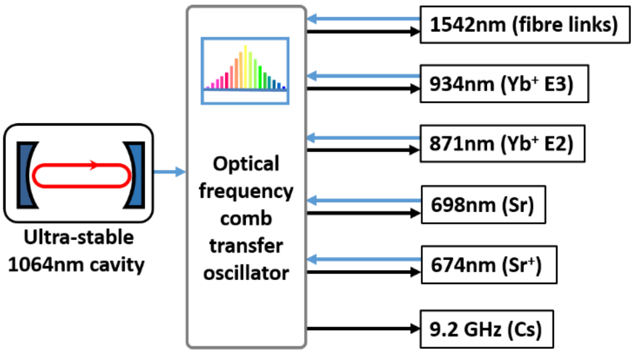


**Figure 1: simplified diagram showing the transfer of stability through the optical frequency comb**

The 1064 nm ultra-stable cavity is based on a 280 mm ULE spacer with fused-silica mirrors and has a measured fractional frequency instability of $5x10^{-16}$ at 1 second. To transfer the stability of the 1064 nm cavity to other wavelengths we use a Menlo Systems fibre-based optical frequency comb centered at 1550 nm, with a 250 MHz repetition rate. The optical frequency comb has 5 independently amplified and wavelength shifted outputs that match the $Sr^+$ clock transition at 674 nm, the Sr clock transition at 698 nm, the first subharmonic of the 435.5 nm E2 clock transition in $Yb^+$, the first subharmonic of the 467 nm E3 clock transition in $Yb^+$, the ultra-stable cavity at 1064 nm, and there is a direct output at 1550 nm for comparisons through optical fibre links.

The optical frequency comb is self-referenced and fully stabilized to a signal from an H-maser, and the transfer oscillator scheme [2] is used to derive virtual RF beats between the lasers of interest and the 1064 nm cavity. The transfer oscillator scheme has the benefit that no re-locking is required should a laser drop out and return. The virtual beat is sent back to the various clock labs and used to improve the stability of their local oscillators. Additionally a signal at 9.2 GHz is generated to be used as the local oscillator in the Cs fountain lab. Using this scheme the Sr lattice clock at NPL has reported a factor of 4 improvement in stability. Improved performance of the other local oscillators, as well as the limits to the performance of the current system will be discussed.

This work was supported by the UK Department for Business, Innovation and Skills as part of the National Measurement System Electromagnetics and Time Programme.

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# High-bandwidth large-dynamic frequency control of an optical comb by tuning polarization state

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High-performance optical frequency combs have been indispensable tools in many applications. Various techniques have been invented to manipulate the repetition rate ($f_r$) and the carrier-envelope-offset frequency ($f_{ceo}$) [1-3]. We report a new servo control method to stabilize comb's frequencies by changing polarization state with a home-made intra-cavity electro-optic modulator (EOM).

The EOM is a 3-mm thick and $5\times5$ mm$^2$ EOM, inserted right after the PBS of a well-known nonlinear polarization rotation mode-locked laser`s loop. The EOM rotates state of polarization about $1.2\times10^{-4}$ rad/v in ellipticity. Repetition rate ($f_r$) of the laser is about is about 192 MHz, and the central wavelength is about 1575 nm.

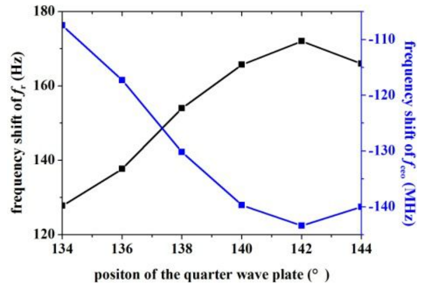


Fig.1: Frequency shifts of $f_{ceo}$ and $f_r$ versus 400 voltage vary applied on the EOM (-200 V to 200 V) with different setting angle of the quarter wave plate near the EOM.

Figure 1 shows the frequency control dynamic range of the frequency comb by tuning the voltage applied on the EOM under different cavity configurations. This dynamic range is two orders of magnitude larger than the traditional intro-cavity EOM method [1], because it benefits from birefringence of the whole cavity instead of only index change of an EOM crystal driven by tunable electric-field. No side effect is observed during experiments.

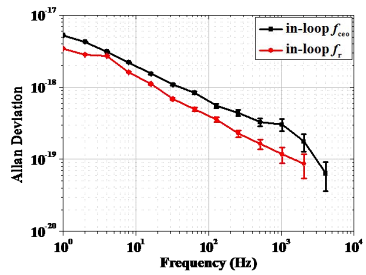


Fig.2: In-loop frequency instability of $f_{ceo}$ (solid black square) and $f_r$ (solid red square).

We have tried to stabilize $f_{ceo}$ and $f_r$ by adding negative feed-back onto the intra-cavity EOM respectively. In-loop frequency instabilities of $f_{ceo}$ and $f_r$ normalized with the reference laser frequency are below $6\times10^{-18}$ at 1 second, and integrate down to low $10^{-19}$ range at $10^3$ second. Details will be reported in the proceeding.

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# Frequency-Tunable Microwave Field Imaging in an Atomic Vapor Cell

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Atomic vapor cell magnetometers are among the most sensitive detectors for magnetic fields, and show promise in applications including materials characterization, in MRI, and for magnetic imaging of the human heart and brain. Tunable atomic magnetometers have previously operated from dc to rf frequencies of a few MHz. We present a continuously frequency tunable microwave magnetometer capable of imaging magnetic fields from GHz to tens of GHz frequencies, representing a four orders of magnitude extension of the atomic magnetometer frequency tunable range. Potential applications include near-field characterisation of microwave circuitry [1], and medical microwave sensing and imaging, where high resolution, intrinsically calibrated atomic sensors could replace bulky and field-perturbing antennas [2]. At fixed microwave frequencies, we have previously used atoms to image microwave magnetic near-fields [1,3,4], and (atom-like) NV centres have recently been used for nanoscale near-field detection and imaging. Microwave *electric* field imaging has also been demonstrated at discrete frequencies using Rydberg atoms. To-date, however, there has been no atomic sensor available for the detection or imaging of arbitrary microwave frequencies, as required for most microwave sensing applications.

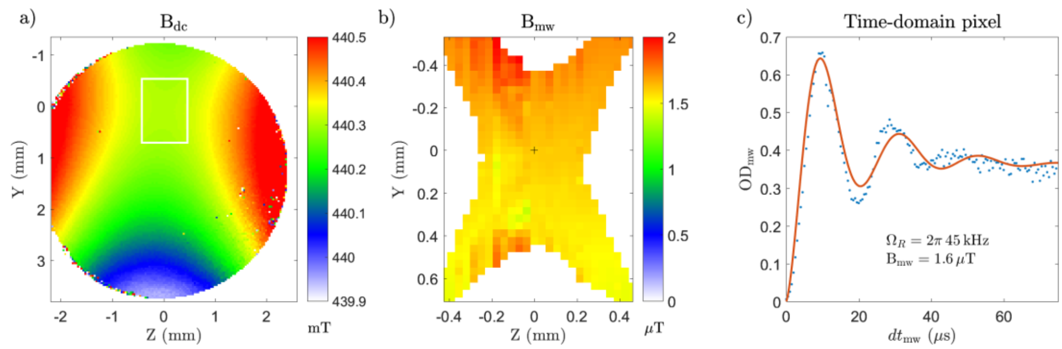


Figure 1: Imaging an 18.003 GHz microwave field: (a) map of the local $B_{dc}$ field extracted from the atomic Zeeman shift; (b) Reconstructed microwave field. The field of view is determined by the $B_{dc}$ inhomogeneity; (c) signal for the pixel marked by a cross in (b), showing Rabi oscillations driven by the microwave.

We detect microwave magnetic fields ($B_{mw}$) through coherent Rabi oscillations driven by the microwave on atomic hyperfine transitions (Fig. 1c). The atomic transitions are sensitive to a narrow microwave frequency band, and we use a large dc magnetic field ($B_{dc}$) to tune the transition frequency to the desired value (Fig. 1a). We work with the $^{87}$Rb hyperfine ground states, however our technique is applicable to any microwave magnetic dipole transition with optical read-out of one of the states, such as other alkali atoms and NV centres.

We also present our progress on developing a frequency-domain EIT measurement of the microwave Rabi frequency, which offers significant improvements in the imaging duty cycle.

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# Development of optical clocks based on strontium atoms: first observed clock-transition spectrum.

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

In our experiment we have about $10^7$ atoms with temperature 2-3μK. Such significant decrease in the temperature of atoms has made implementation of capturing atoms to an optical lattice on magic wavelength of 813 nm possible. For these purposes, a commercial laser TOPTICA with outgoing radiation power of 1.5 W was used. Laser's radiation is directed into the polarization-maintaining fiber and is focused into a cloud, with a beam waist diameter about 60 μm. The described configuration allows obtaining about 1% of atoms in the optical lattice.

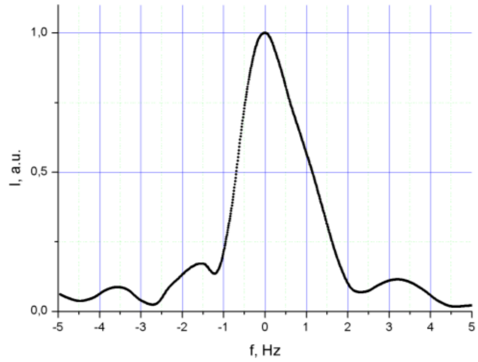


Fig. 1: Beat note signal between two clock lasers (FWHM=1.75 Hz).

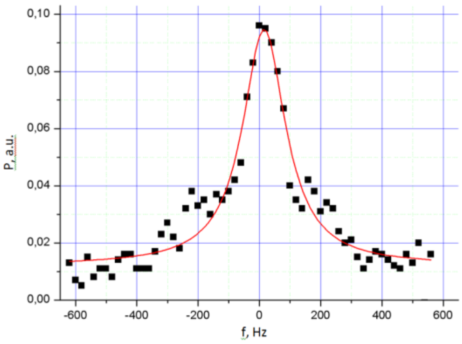


Fig. 2: Spectrum of the $^1S_0$-$^3P_0$ transition.

A narrow-line laser system for spectroscopy of clock transition based on ULE cavity has been developed and investigated. The linewidth of beat note between two similar laser systems is about 1.75 Hz (Fig. 1) with a frequency drift 0.11 Hz/s. Frequency tuning has made by a femtosecond laser system. It allows us to decrease scan range to several kHz. We excite the $^1S_0$-$^3P_0$ clock transition in $^{88}$Sr with the technique of magnetic field-induced spectroscopy. At the moment we have linewidth about 100Hz (Fig. 2) and we try to optimize our setup configuration to decrease it. In our lab we also have built a second similar system. So in nearest future we plan to lock our ultrastable lasers to clock transition and make comparisons between them.

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# Time Transfer over a White Rabbit network

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Time transfer through optical fiber links has gained significant recognition in the past few years, following the impressive developments in the area of frequency transfer over the last decade. Today, a very promising direction for time transfer is the implementation of White Rabbit PTP (Precision Time Protocol) technology [1] on wide area networks. White Rabbit is a novel technology developed at CERN, based on PTP using Synchronous Ethernet and other techniques to achieve high performance. It demonstrates sub-nanosecond time stability and synchronization of arrays of instruments over 10-km scale networks. The challenges are the extension to longer distances [2] and the development of absolute time calibration [3].

In view of time dissemination on active telecommunication networks, we are exploring uni-directional configurations for White Rabbit links [2]. Our objective is the development of a scalable and compatible network time transfer approach providing multiple user dissemination, competitive with GNSS-based time distribution. Our first trial uses White Rabbit for short range time dissemination inside Paris Observatory's campus, on a mid-range fiber link. Our experimental schematic is shown in Fig 1. We will present experimental characterizations of phase noise, Allan deviation and time stability of commercially existing White Rabbit solutions, for uni- and bi-directional topologies, and our progress towards precise time transfer.

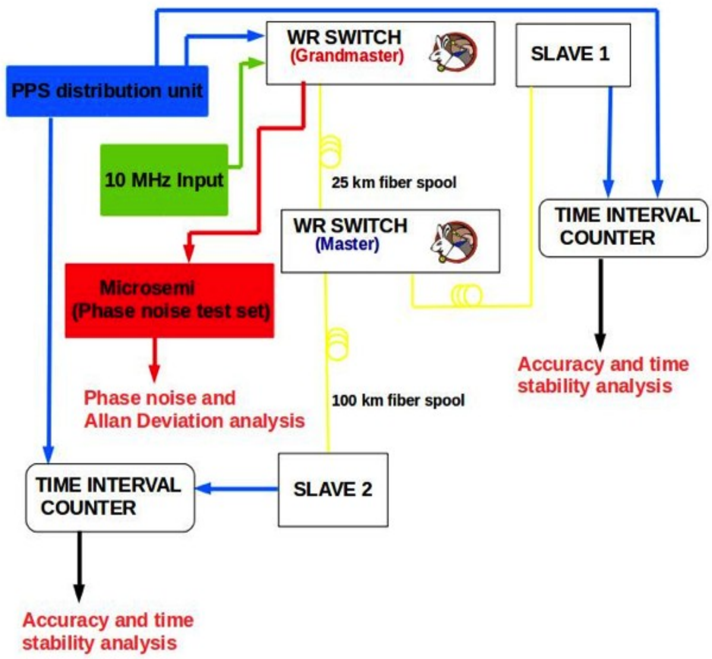


Figure 1. Experimental setup.

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# Temperature and Current Dependence of 1/f Frequency Noise in Narrow-Linewidth Discrete-Mode Lasers

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For the majority of semiconductor lasers, the integral noise features such as the linewidth and RIN are defined by flicker (1/f) noise contribution, which is believed to be due to generation-recombination processes through recombination centers in defects (e.g. dislocations). Very little attempts were reported in literature to build a comprehensive theory for flicker noise in semiconductor lasers. E.g. Ref. [1] provides only a model for RIN while we did not find a rigorous model for the flicker frequency noise (FN). In this communication we report on 1/f FN dependence on the cavity length, driving current and temperature of the narrow linewidth Discrete Mode Laser Diodes (DMLD).

The active region of our DMLD comprises six AlGaInAs quantum wells. Single wavelength operation is achieved by introducing shallow-etched DBR-like features [2]. DMLD samples with cavity length from 1.5 to 3 mm have been fabricated and tested. Measured coefficient $h_{-1}$ which is the FN PSD extrapolated to the Fourier frequency of 1 Hz, exhibits a minimum [Fig.1(a), left axis], where all laser samples show narrowest linewidths. Analyzing this behavior, we conclude that the product of squared linewidth and current $FWHM^2 \cdot I$ reveals the flicker FN variations [Fig.1(a), right axis]. Therefore we study the current and temperature dependence of flicker FN by measuring this parameter. Fig.1(b) shows the results obtained for three different pump currents (curves) and temperatures (see data labels). There is an optimal operation point with the lowest flicker FN, which is at 200 mA and 30°C in the particular sample. The location of local minima shifts symmetrically with the laser temperature and/or current detuning. Such behavior cannot be attributed to generation-recombination processes. This behavior much resembles the lasing mode pulling from the DBR mode due to the spectral gain profile and DMLD cavity. Indeed, we find that 1/f FN is correlated with the wavelength difference of the lasing mode and the power-weighted mean wavelength of the amplified spontaneous emission into other cavity modes [Fig.1(c)]. We believe we bring an important piece of experimental data that allows one to build a realistic model for the frequency flicker noise in a semiconductor laser.

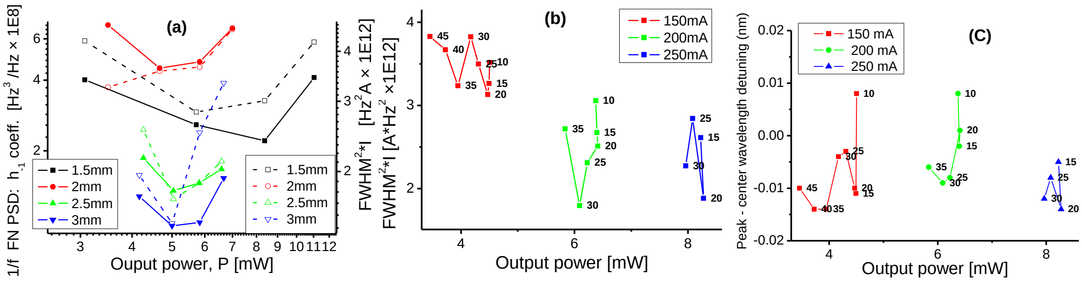


Fig. 1: (a) Measured 1/f FN PSD (left axis, closed symbols) and a product $FWHM^2 \cdot I$ (right axis, open symbols) vs output power in DMLDs of cavity length from 1.5 to 3 mm. (b) Parameter $FWHM^2 \cdot I$ indicating FN PSD vs output power in 1.5 mm long DMLD at different temperatures (labels shows °C) and currents (curves). (c) Peak-center wavelength difference vs power in same conditions as in (b).

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# A method to verify the P1-P2 hardware calibration in GNSS receiving systems dedicated to Time Transfer

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Remote atomic clock comparison is essential for time and frequency metrology. A classic way is to use the measurements of Global Navigation Satellite Systems (GNSS) to determine the synchronization differences between the local clocks and the GNSS system time. Combining these differences simultaneously in two stations provides the differences between the clocks of the stations.

However, the hardware delays of the signals across the GNSS receiving system (antenna, cables and receiver) have to be determined by calibration before using the GNSS measurements for accurate time transfer and time dissemination. The receiver and antenna contribution to the hardware delays are frequency-dependent.

The HW delays in GNSS equipment of the time laboratories participating to the TAI are based on differential calibration, following the guidelines established by the CCTF Working Group on GNSS Time Transfer [1]. In this procedure, some traveling systems serve as a transfer between reference stations (named as "Group 1 laboratories") and the visited stations to be calibrated (named as "Group 2 laboratories"). The reference values are provided by a set of systems operated in the Group 1 laboratories and at the BIPM [2].

If there is a bias in the reference values then the same bias will appear in all the systems calibrated within the calibration campaigns organized by the BIPM or the Regional Metrological Organization (RMO) following the guidelines. In a time transfer solution between two stations so-calibrated, the common bias will be eliminated. However in some cases the bias will not be eliminated. This will be the case e.g. when only one station so-calibrated is used to have access to the GNSS time, or in a time transfer solution where the second station is calibrated using a different way, e.g. an absolute calibration.

In this study we propose a strategy to verify the consistence between the reference values used for the different frequencies (GPS P1 and P2 in this case). Using the recent calibration results [2] we demonstrate that the reference values are consistent below the ns level.

Furthermore, due to aging, the GNSS station hardware delays can vary with time so that regular calibration should be operated. We applied our proposed strategy to monitor the stability of the inter-frequency delays. We show that some station can have significant drift in the hardware delays which are not similar on the two GPS frequencies.

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# High-Contrast Bright-Type Magneto-Optical Resonances in Buffer-Gas or Antirelaxation-Coated Vapour Cells

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New method for observing magneto-optical subnatural-width resonances in the Hanle configuration is theoretically and experimentally studied. These resonances appear in absorption or fluorescence of vapour cell, when magnetic field is being scanned. The sign of the resonances depends on various factors: values of total angular momenta of driven atomic transition, orientation of magnetic field, etc. Here we focus on the resonance of "bright" type – electromagnetically induced absorption (EIA), which can be observed as a spike in absorption of the light wave passed through a vapour cell. In contrast to "dark" resonances of electromagnetically induced transparency (EIT), resulted from the coherent population trapping [1] in atomic ground state, resonances of "bright" type have not achieved widespread use. The main reason is that these resonances cannot be observed simultaneously with good contrast (tens of percent) and narrow width (1 kHz or less) in widely used standard schemes [2,3]. In those schemes EIA is due to the spontaneous transfer of anisotropy from the excited state to the ground one [4]. Therefore, when buffer-gas or antirelaxation-coated cells are exploited, it does not lead to improving the properties of EIA (in contrast to EIT). It is due to collisional destroying the atomic excited-state anisotropy. Some other "non-standard" EIA observing schemes either are quite complicated or do not show acceptable values of width and contrast.

In ref. [5] we developed the polarization method for controlling a sign of the subnatural-width resonance (EIT↔EIA). Then we supposed that the method could be exploited for observing EIA with good properties, because it allows one using all those ways for improving resonance, which have already showed their very good sides in the cases of EIT. In this work, besides developing the detailed theoretical model for high-contrast EIA in the new scheme, we have also carried out experiments with transition $F_g=1 \rightarrow F_e=1$ in $D_1$ of $^{87}$Rb. The results obtained can be interesting for quantum magnetometry and for producing sensitive magneto-optical switch for controlling the light-field intensity in optical communications.

This work was partially supported by the RFBR (15-02-08377, 15-32-20330, 14-02-00712, 14-02-00939), the RF Ministry of Education and Science (order no. 2014/139, project no. 825), Presidium of the SB RAS. M.Yu. Basalaev was also supported by the RFBR personal grant. Ch. Andreeva was supported by the scientific exchange project "COSMA" in the frame of the 7th European Framework Programme (FP7-PEOPLE-2009-IRSESM).

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# The Matter-wave laser Interferometric Gravitation Antenna (MIGA) Project: new perspectives for high precision gravity measurements

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The Matter-wave laser Interferometric Gravitation Antenna (MIGA) project aims at demonstrating precision measurements of gravity with cold atom sensors in a large scale underground instrument and at studying the associated powerful applications in geosciences and fundamental physics [1]. The first stage of the project (2013-2018) will consist in building a 300-meter long optical cavity to interrogate atom interferometers and will be based at the low noise underground laboratory LSBB based in Rustrel, France. The second stage of the project (2018-2023) will be dedicated to science runs and data analyses in order to probe the spatio-temporal structure of the local gravity field of the LSBB region, which represents a generic site of hydrological interest.

MIGA will also assess future potential applications of atom interferometry to gravitational wave detection in the frequency band ~ 0.1 − 10 Hz hardly covered by future long baseline optical interferometers [2]. This poster will describe the targeted applications of MIGA in geosciences and Gravitational Wave detection and present the status of the construction of the MIGA sub-systems.

The atomic sources are realized from 2D and 3D $^{87}$Rb Magneto-Optical Traps. The atoms are launched in a moving molasses before been selected in the state F=2, $M_F = 0$ and on velocity along one of the horizontal directions by Raman transitions. The interferometers are based on two photon Bragg transitions to manipulate the atomic wave packets. Different sources of atoms will share the same light pulses with distance up to 300 meters and will lead to differential measurement sensitive to gradient of acceleration and/or time fluctuation along the horizontal axis.

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# Sub-nanosecond synchronization accuracy for time-sensitive applications on Industrial networks

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White Rabbit (WR) is a technology born at CERN able to provide sub-nanosecond accuracy for time and frequency transfer using standard PTP and Synchronous Ethernet (SyncE) [1]. WR was designed to be the main time provider system for scientific infrastructures such as particle accelerators and colliders.

This contribution proposes a change of approach for the WR PTP distribution to become a timing solution with strong focus on engineering frameworks, such as Smart Grid. This approach includes a new design following IEC 61850 [2], where new developments make possible for WR devices to work as Transparent Clocks (TCs) instead of Boundary clocks (BCs) as in the case today. This maximizes the interoperability with other industrial devices and, at the same time, the utilization of TCs offers better synchronization results since PTP messages include the entire network delay considering all TCs as a unique fiber.

WR currently uses an end-to-end (E2E) mechanism to distribute PTP. The development of a WR-TC device for big infrastructures suggests a peer-to-peer (P2P) mechanism (Fig.1) in which every middle node forwards *sync* and *follow_up* messages including the residence time of the sync message while passing through the TC. Using TCs for time and data propagation also opens the doors to high-availability and fault tolerance features for mission-critical and time-sensitive applications [2]. It supports the development of redundancy protocols, such as HSR or PRP to guarantee the delivery and reception of critical services such as timing and substation events (GOOSE, GSSE, SMV).

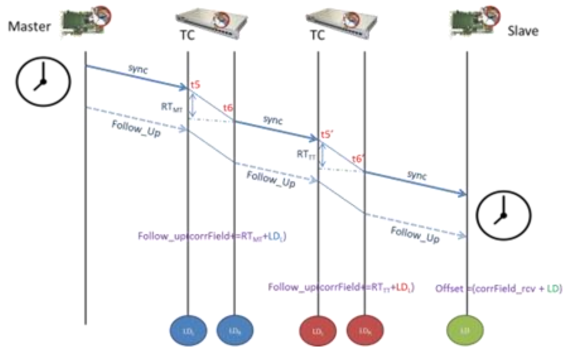


Fig. 1: White-Rabbit P2P. PTP frames are forwarded from the master to the slave considering middle hops as a single fiber link.

Finally, P2P approach offers a better synchronization mechanism to avoid synchronization loss of middle nodes and also supports the development of redundancy protocols to make possible the migration of WR to industrial networks.

In this contribution we present the modifications done at the original WR protocol to support these TC capabilities, evaluate the impact in performance and review the benefits of the proposed approach.

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# Synchronous mode-locked laser network with few-fs jitter and multi-km distance

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Mode-locked lasers generate optical pulse trains with ultralow jitter in the attosecond regime [1]. Drift-free transmission of these stable timing signals to other external lasers is particularly important for pump-probe experiments aiming for high temporal resolution [2] and synchronization of distant optical clocks [3]. Here we report a multi-km-scale synchronous mode-locked laser network with 1.4-fs RMS total jitter over 40-h operation.

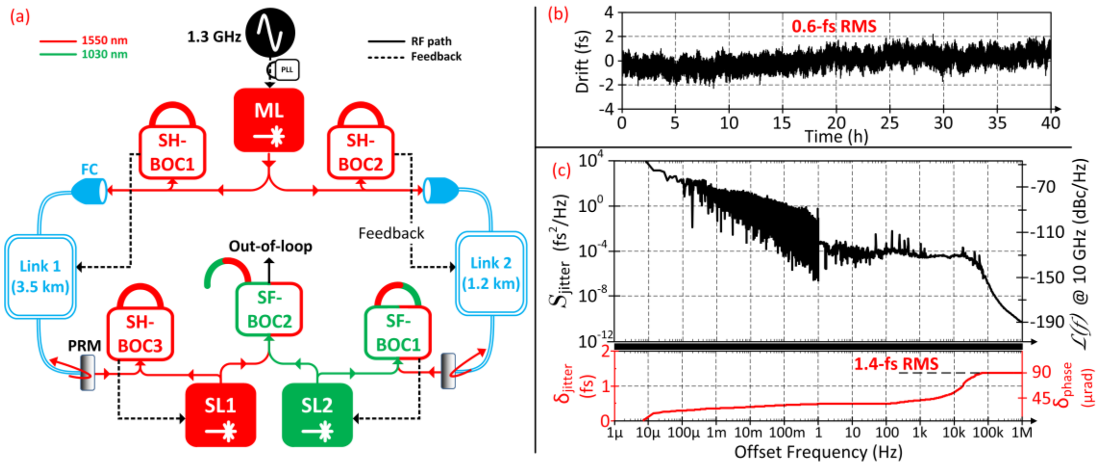


Fig. 1: (a) Schematic of the experimental setup (b). Out-of-loop timing drift between two independently synchronized lasers. (c) Out-of-loop jitter spectral density $S_{jitter}$ and its integrated timing jitter $\delta_{jitter}$. Right axes show equivalent SSB phase noise $\mathcal{L}(f)$ and integrated phase $\delta_{phase}$ at 10 GHz carrier frequency.

Our master laser (ML) is a mode-locked laser operating at 1554-nm center wavelength with 216.67-MHz repetition rate locked to a microwave reference. As shown in Fig. 1(a), output of the ML is split into two separate timing links with a total length of 4.7 km. Each link consists of a polarization-maintaining (PM) dispersion-compensated fiber spool, a PM fiber stretcher, a motorized delay stage and a bi-directional PM fiber amplifier. A partially reflecting mirror (PRM) at the end of each link back-reflects 10% of the optical power to the link input. The reflected pulses are then combined with fresh pulses from the ML in the second-harmonic (SH) balanced optical cross-correlators (BOC). SH-BOC1 and SH-BOC2 measure the propagation delay fluctuations in the links and generate error voltages applied to the fiber stretchers and the motorized stages to compensate for the fast jitter and long-term drift. Finally, timing stabilized outputs of the links are used for synchronizing two remote mode-locked lasers (SL1 and SL2) operating at different central wavelengths (1550 nm and 1030 nm). SH-BOC3 locks SL1 to Link 1 output via its intracavity PZT; whereas a sum-frequency (SF) BOC between 1030 nm and 1550 nm (SF-BOC1) is built to synchronize SL2 with Link 2 output. In order to evaluate the timing precision of the synchronous laser network, the outputs of SL1 and SL2 are combined in free-running SF-BOC2. Relative timing stability is monitored for 40 h without interruption (see Fig. 1(b)) and the residual drift below 1Hz is only 0.6 fs RMS. Complete jitter spectral density is shown in Fig. 1 (c). The integrated jitter from 7 µHz up to 1 MHz is only 1.4 fs, corresponding to $9.72 \times 10^{-21}$ relative timing instability.

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# Using GaN for MEMS: from material to resonators and sensors

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Gallium Nitride has become in the past decade a widely studied material for optoelectronics, power electron devices, and RF transistors. In the field of electromechanical devices, GaN offers a broad range for microsystems [1]. This is because it gathers unique semiconducting properties and piezoelectricity, which offers a platform for realistic co-integration strategies [2]. Moreover, the wide bandgap of GaN makes it promising for MEMS operating in harsh conditions [3].

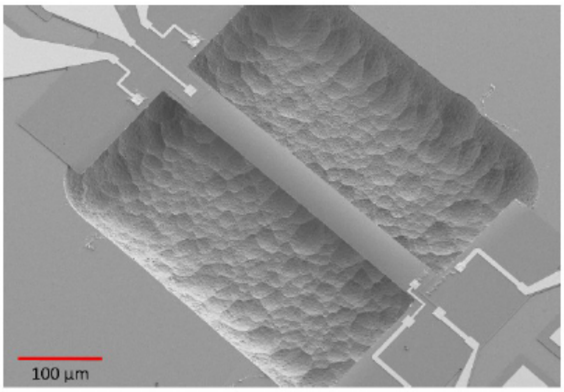


Fig. 1: Gallium Nitride MEMS resonator fabricated on a 700 nm thick epilayer. The device takes advantage of the 2D electron gas for actuation and detection.

Here we will present an overview of our work toward high performance MEMS resonators and sensors. First, we will show that developing specific epitaxial growth enables MEMS designer to go beyond the current limitations of commercially available material. In particular, we were able to demonstrate ultrathin buffers under 1µm thickness where the AlGaN/GaN heterostructure properties, Young modulus, and careful tuning of stress distribution are validated for device processing [4]. We will report on our design and process of resonators with integrated transducers on these epilayers. The study of piezoelectric actuation, 2DEGs piezo-amplified detection in 3 terminal or 2 terminal tranducers will be described and in particular the understanding of frequency variations upon bias conditions. In conclusion, we will assess the capability of GaN for MEMS accelerometers operating with wide range and resolution under $5mg/Hz^{1/2}$.

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# Optical atomic clock measurements in $^{171}Yb^+$

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Singly-ionised ytterbium ($^{171}Yb^+$) possesses two optical clock transitions: an electric quadrupole (E2) transition at 436 nm [1] and an electric octupole (E3) transition at 467 nm [2], that have both been accepted as secondary representations of the SI second, with projected systematic uncertainties at the $10^{-17}$-$10^{-18}$ level. The E3 transition has a nHz-level natural linewidth and very low sensitivity to electric and magnetic fields making it a strong candidate for a re-definition of the SI second.

We report on advances in the understanding and control of all systematic perturbations. Construction and characterisation of a new single-ion trap have reduced the time-dilation and dc Stark shifts caused by excess micromotion, and are stable over extended periods to the $10^{-19}$ level [3]. The electric quadrupole shift has been reduced by two orders of magnitude compared to existing traps at NPL. Magic wavelength and IR Stark shift measurement are underway which should reduce the uncertainty on the blackbody radiation induced frequency correction to below $1 \times 10^{-18}$.

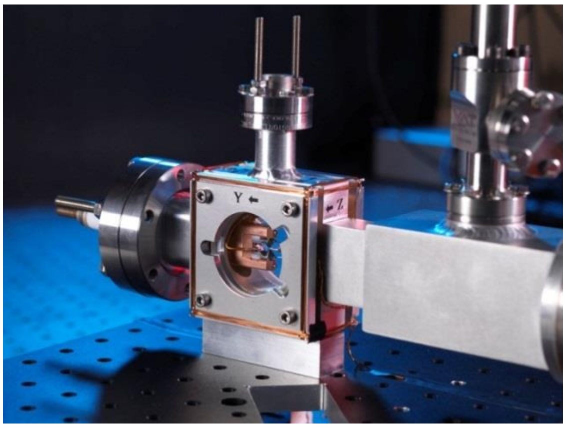

Fig. 1 New $Yb^+$ endcap trap which exhibits greatly reduced micromotion and BBR shifts.

The E3 transition clock laser has been stabilized to a new 30 cm-long ULE cavity with a theoretical thermal noise limit at the $1x10^{-16}$ level. The clock has been operated with few-Hz level transition linewidths greatly improving the system stability and reducing the averaging time required to reach the clock's systematic floor.

The $^{171}Yb^+$ clock has been used to measure a number of frequency ratios, both locally with other optical clocks at NPL, and internationally via broadband two-way satellite time and frequency transfer. Improvements to the robustness and reliability of the system enabled an 80% uptime during a four week measurement with continuous datasets of more than $10^5$ seconds routinely collected.

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# A Study on Reducing the Diurnal in the Europe-to-Europe TWSTFT links

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Two-way Satellite Time and Frequency Transfer (TWSTFT or TW) is used by many international timing laboratories in comparing their clocks and in contributing their timescale data to the generation of International Atomic Time (TAI) and Coordinated Universal Time (UTC). However, most of the TWSTFT links exhibit a daily variation (diurnal) on the order of 1 ns in the TWSTFT differences. The stability of TWSTFT is degraded by the diurnal. Many studies on the sources of diurnal have been carried out, but no dominating cause of the diurnal has been found.

In this study, we report that the diurnal in the Europe-to-Europe TWSTFT links can be reduced by using the triangle difference of the transatlantic TWSTFT differences. Figure 1 shows that the diurnal of the PTB-OP link is greatly reduced with the triangle difference of the NIST-PTB and NIST-OP transatlantic TWSTFT differences. Figure 2 shows the Time Deviation (TDEV) of the direct and triangle PTB-OP differences. Notice that the triangle difference also reduces the short-term transfer noise observed in the direct difference. In this paper, we will examine the triangle difference for several Europe-to-Europe links and analyze where the improvement comes from.

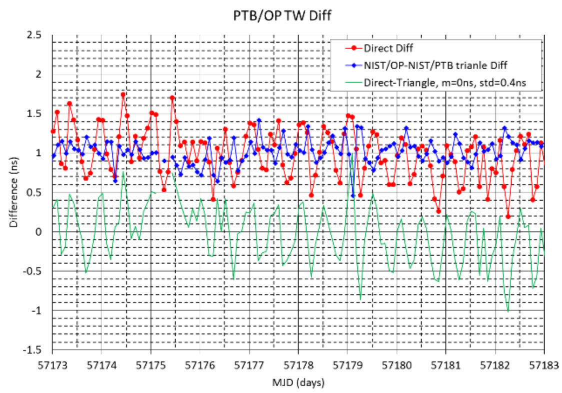


Fig. 1 Example of a 10-day Direct and Triangle TWSTFT Differences for the PTB-OP link.

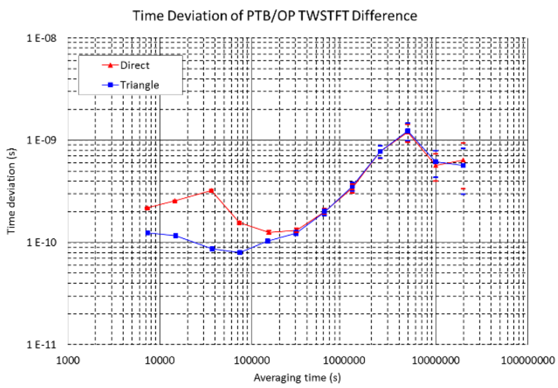


Fig. 2 TDEVs of the Direct and Triangle TWSTFT Differences computed from MJD 56619 to MJD 57308 for the PTB-OP link.

# Light Shifts Studies in CW and Ramsey Double Resonance Vapor Cell Frequency Standards

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We report our investigations on a compact high-performance rubidium (Rb) vapor-cell atomic clock based on microwave-optical double-resonance (DR). These studies are performed in both DR continuous-wave (CW) and Ramsey-DR schemes. The same Physics Package (PP) with the same Rb vapor cell and a magnetron-type cavity with only 45 $cm^3$ external volume were used for the measurements. The Rb vapor cell has a new design with 10 times smaller stem, resulting in about one order of magnitude reduction of the stem temperature coefficient when compared to previous cell realizations [1, 2]. The current clock's PP has a volume of only 0.8 liters, including temperature control and magnetic shields. This clock's PP is completed by a newly-developed frequency-stabilized laser head [3] with 1 liter volume of the optical setup, using a distributed feedback (DFB) laser diode and an acoustic optical modulator (AOM) integrated within the laser head for switching the laser output.

In CW-DR, optical pumping, microwave interrogation, and optical detection are all applied simultaneously, while for Ramsey-DR these three processes are separated in time. In the CW-DR scheme, first results demonstrate a DR signal with a contrast up to about 30% and a linewidth of about 400 Hz. In Ramsey-DR mode, central Ramsey fringes with contrast of up to 35% and a linewidth of 160 Hz have been observed. In both schemes, short-term clock stabilities of about $3\times10^{-13}\ \tau^{-1/2}$ are measured. In the Ramsey-DR operation, optical and microwave interactions are separated in time, and therefore the light-shift effects are suppressed by more than one order of magnitude. Both the intensity and frequency light-shifts were studied for different laser frequency detuning, by means of stabilizing the laser to different reference transitions, and will be presented at the conference. This allows for improved long-term stability of the Ramsey clock compared to CW-DR.

Acknowledgement

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# Progress towards a $^{88}Sr^{+}$ single-ion clock with a fractional uncertainty at the $3 \times 10^{-18}$ level

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In recent years, a few optical clocks based on either single ions or neutral atoms in optical lattices have reached or surpassed the $10^{-17}$ fractional uncertainty level, outperforming the evaluated uncertainty of the best cesium fountain clocks that realize the SI second by more than one order of magnitude [1]. The optical frequency standard developed at the National Research Council of Canada, based on the $5s\,^2S_{1/2}$–$4d\,^2D_{5/2}$ transition of a single ion of $^{88}Sr^{+}$, has a fractional uncertainty evaluated at $1.2 \times 10^{-17}$ as reported in Table 1.

The key methods developed to control the systematic shifts of the *S–D* transition to this low level are the electric quadrupole shift cancellation method based on averaging the Zeeman sublevel energies of the *D* state [2], a high-accuracy measurement of the differential scalar polarizability $\Delta\alpha_0$ of the clock transition [3], and the operation of the trap at a special rf frequency that suppresses the micromotion shifts by a factor of 200 in addition to the usual minimization using trim electrodes [3]. Table 1 shows that the main source of uncertainty is the evaluation of the blackbody radiation (BBR) field that contributes a fractional uncertainty of $1.1 \times 10^{-17}$. Since the next leading sources have a fractional uncertainty of $2 \times 10^{-18}$, improvements to the BBR field evaluation will have a strong impact on the overall uncertainty evaluation. We estimate that a new evaluation of the trap component temperatures using a thermographic camera and a dummy trap that is a close copy of that used in the frequency standard system should allow reduction of the BBR field contribution to $\approx 2 \times 10^{-18}$, and the overall uncertainty to $\approx 3.4 \times 10^{-18}$ [4]. For this estimate, it is assumed that the 1092 nm light shift has been eliminated since the origin of the current light shift is due to modifiable technical limitations in the current light shuttering system. The stability of our $^{88}Sr^{+}$ clock now reaches a level of $3 \times 10^{-15}/\sqrt{\tau}$, suitable for $^{88}Sr^{+}$ ion clock comparisons at the $10^{-17}$ level in about two days of averaging time [5].

Table 1: Simplified uncertainty budget of the NRC $^{88}Sr^{+}$ ion *S–D* frequency standard.

| Source | Fractional |
|---|---|
| BBR field evaluation | $1.1 \times 10^{-17}$ |
| BBR coefficient ($\Delta\alpha_0$) | $8.3 \times 10^{-19}$ |
| Excess micromotion | $1 \times 10^{-19}$ |
| 1092 nm ac Stark shift | $2 \times 10^{-18}$ |
| Second-order Doppler (thermal) | $1 \times 10^{-18}$ |
| Electric quadrupole shift | $3 \times 10^{-19}$ |
| Collisional shift | $2 \times 10^{-18}$ |
| Total uncertainty | $1.2 \times 10^{-17}$ |

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# Microwave Cavity Characterization for Rubidium Frequency Standards

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We report investigations on a new and modified magnetron-type microwave cavity [1] to operate at the frequency of 6.834 GHz corresponding to the hyperfine ground-state transition of Rubidium 87. This new cavity has an outer volume of 45 $cm^3$ and integrates a Rb vapour cell with the length and diameter of 25 mm, and with a reservoir stem of reduced volume, resulting in a temperature coefficient of the cell stem reduced by one order of magnitude compared to our previous cell realizations. In view of applications in high-performance Rb atomic clocks, the properties of the cavity resonance were studied as a function of temperature. In particular, the resonance frequency with temperature was found to be on the level of 70 kHz/K, sufficiently low to avoid clock instabilities arising from cavity pulling effects.

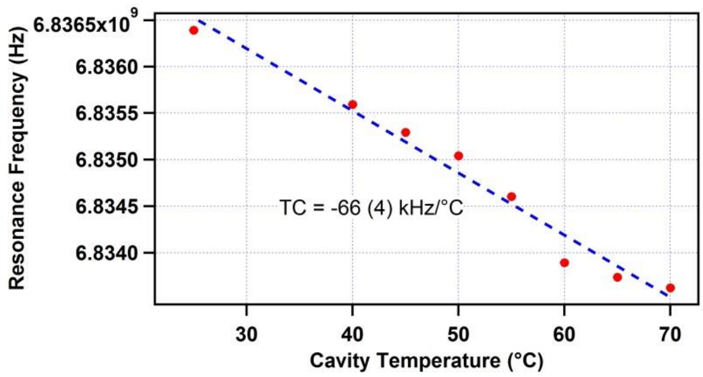


Figure. Measured cavity temperature coefficient.

Parametric studies based on a full-wave Finite Element Method (FEM) simulation were performed to obtain predictions on the temperature tuning of the cavity, and shed light on the influence of effects such as the temperature effect of the electrodes, the tuning mechanism, the coupling and the thermal expansion of the vapor cell. Our work is relevant for general understanding of the temperature influence on the resonance frequency in cavities based on loop-gap structures and $TE_{011}$-like mode.

Acknowledgement

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# Relaxation Time Measurements in a Rb Vapor Cell

Mohammadreza Gharavipour[1], Ivan S. Radojičić[2], Florian Gruet[1], Christoph Affolderbach[1], Aleksandar J. Krmpot[2], Brana M. Jelenković[2] and Gaetano Mileti[1]

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We are studying the physics of compact atomic frequency standards (atomic clocks) based on $^{87}$Rb vapor cells, in view of the development of novel high-performance atomic clocks for applications such as satellite navigation systems or industrial metrology applications. In our studies we use a clock physics package based on a compact magnetron-type cavity (external volume of only 45 $cm^3$) and a buffer-gas vapor cell of 25 mm diameter and length [1]. The magnetron-type cavity has been extensively studied (both in theory and experiment) and demonstrated an excellent uniformity of the microwave magnetic field orientation as well as a sufficiently homogeneous field amplitude distribution inside the cavity [2]. We apply laser optical and microwave signal interrogation of Rb atoms, and have successfully achieved state-of-the-art short-term stability performances for the laser pumped Rb atomic clocks based on both continuous-wave (CW) and pulsed optical pumping (POP) schemes [2, 3].

Here we report results of different methods for measurements of relaxation times (T1 and T2) of the 87 Rb clock transition in the Rb vapor cell. The traditional Franzen method [4] of evolution in the dark is used to measure population relaxation time T1. Continuous-wave laser-microwave double resonance spectroscopy can deliver T2 relaxation times. Two variants of the Ramsey scheme are also used to measure both population and coherence relaxation times, T1 and T2 respectively. In this scheme, two $\pi/2$ microwave pulses are introduced between pump and probe laser pulses of the Franzen sequence. The first microwave pulse creates a coherent superposition of the two hyperfine F = 1, 2 states. Then during the Ramsey time the atomic superposition state accumulates a phase relative to the microwave local oscillator. The second microwave pulse converts this phase in to a population difference between hyperfine states. These measurements result in relaxation times $T1 \approx T2 \approx 3.5$ ms, which are consistent with the theoretical expectations.

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# Yb optical lattice clock with $10^{-18}$-level standard uncertainty

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Recently, optical lattice clocks have demonstrated fractional instability at the $10^{-18}$ level [1,2,3]. Here, we report efforts for improving stability of the NIST Yb optical lattice clock with $\leq 1 \times 10^{-16}/\sqrt{\tau}$ level, for averaging time in seconds. Furthermore, we provide an update on recent work extending the systematic uncertainty evaluation to the $10^{-18}$ level. We have carried out a detailed investigation into residual Doppler shifts which could otherwise compromise accuracy of a lattice clock. Additionally, we describe optical lattice tunneling considerations, and recently implemented sideband cooling mechanisms [4] yielding axial atomic temperatures < 1 μK, which can significantly suppress tunneling frequency shifts. We also highlight detailed studies of Stark shifts due to the optical lattice, yielding a precise characterization of lattice polarizability, hyperpolarizability, vector Stark, and M1/E2 contributions. In addition, we have improved measurements of the probe AC Stark shift and second-order Zeeman shift, and report our current total systematic uncertainty in the low $10^{-18}$ level.

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# Carrier-Phase Two-Way Satellite Frequency Transfer between OP and PTB

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We demonstrate advanced two-way satellite frequency transfer using the carrier-phase information (TWCP) between OP and PTB. NICT has developed a TWCP technique and reached a lower instability for frequency comparisons at short averaging times in the $10^{-13}$ range [1]. To employ this technique, an arbitrary waveform generator and an AD sampler developed by NICT were installed into earth stations at OP and PTB. The measurement was performed once every 2 hours using a 200-kHz bandwidth signal on a satellite link where regular TWSTFT measurements are performed among metrology institutes in Europe. A short-term stability of $2 \times 10^{-13}$ at 1 s was obtained.

Frequency up/down converters are key devices for TWCP whose phase stability in frequency conversion has an impact on the TWCP solution. We evaluated setups with converters located indoor and outdoor. It was found that indoor frequency converters were more suitable for TWCP because of their sensitivity to temperature variation and instability of the external reference signals. Stable environmental conditions and reference signal distributions were identified as the most crucial points and more careful attention should be paid to them in future experiments.

Atomic fountain frequency standards are operated almost continuously at OP and PTB where the frequency differences are routinely measured with respect to a reference hydrogen maser and UTC(PTB), respectively. We measured the frequency differences between the OP reference maser and UTC(PTB) by TWCP, and for comparison, by relating their frequencies to the local fountains. In this report, the evaluation and comparison results are presented.

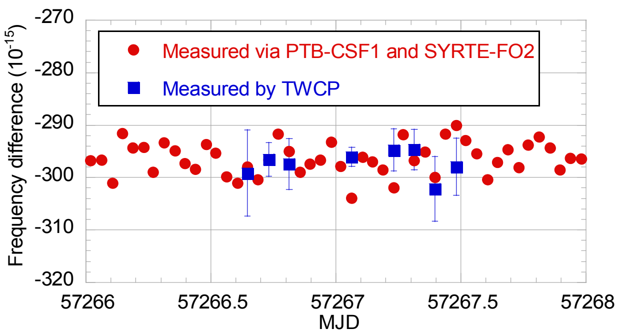


Fig. 1: Frequency differences between UTC(PTB) and a reference hydrogen maser at OP measured via PTB-CSF1 and SYRTE-FO2 fountains, respectively, and by TWCP. For the fountain measurements mean values over one hour are shown. Each TWCP measurement was performed for about 3000 s every two hours. The error bars indicate the modified Allan deviation at an averaging time of 512 s.

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# The Development of GPS/BDS Time Transfer System

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With the development of GNSS, Beidou system plays a more important role on PNT (Positioning Navigation and Timing) in China. The new rinex file format v3.03 and upgraded CGTTS file V3 format are extended to include Beidou system. But most GNSS time transfer systems do not cover Beidou system. BIRM has developed a GNSS time transfer system which supports both GPS and Beidou system.

This paper describes the development of the hardware system and the data processing software of the GPS/BDS time transfer system. For Beidou system, most GPS data processing methods are applicable, but some points must be noticed. First, the calculation of model ionospheric delays for BDS is difference from GPS, the parameters in the navigation message are with respect to B3 signal. Second, after the delays of local time to BDS system time from all the Beidou SVs have been got, the average method is different from GPS, since Beidou constellation is consist of different types of satellite, which include 5 GEO, 5 IGSO and 4 MEO satellites.

Through the interface of the software, all the pseudorange and carrier phase observations for each second from GPS L1/L2 and BDS B1/B2 could be monitored. CGTTS V3 format files for GPS and BDS could be generated, and Rinex v3.02 observation (30s) files for GPS and BDS could be recorded.

The results from GPS and Beidou system are compared. The precision from GPS is better than Beidou about 50%. By analyzing the error source, the differential code biases (DCB) of Beidou satellites make great contribution to the uncertainty. To improve the precision of BDS, the Beidou Satellite DCBs should be further studied.

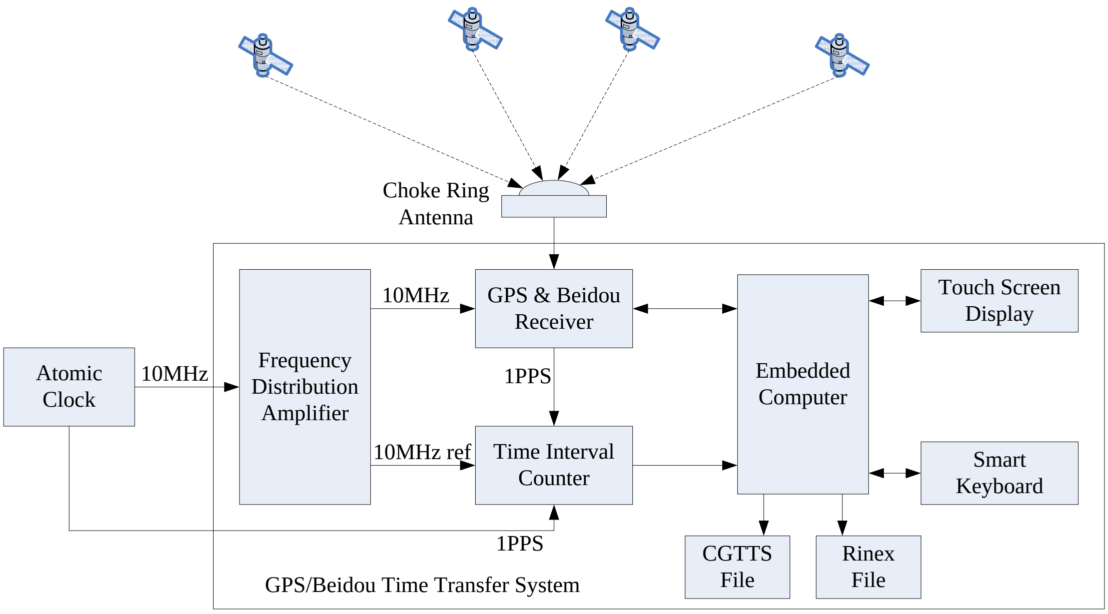


Figure 1 Block diagram of GPS/BDS time transfer system

# Determination of differential delays of earth stations in Paris and Torino from the calibrated OP-IT TWSTFT link

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Two-Way Satellite Time and Frequency Transfer (TWSTFT) technique [1] is used in most of the national metrology institutes (NMIs) or Designated Institutes (DIs) as the primary link method for time-scales comparisons. A major advantage of this technique is direct comparisons of time-scales in almost real time using remote earth stations in microwave links through a geostationary satellite. A best link quality can be achieved in reducing residual non-reciprocal effects, using well-characterized earth stations and improved carrier-to-noise ratio of two-way links during measurement within time-slots period for which the transponder is less busy on a regular basis over an appropriate period of time.

Four Ku-band TWSTFT earth stations equipped with four SATRE modems, implemented in LNE-SYRTE (Paris) and INRIM (Torino) are used: OP01, OP02, IT01 and IT02 (Fig. 1). Different pseudo-random noise codes at 1 Chip/s and modulated signals frequencies are applied. Measurements are performed on time slots of two minutes per each link, and then repeated every two hours. The differential delays of each pair of stations are thus determined from measurements of the various two-way links, relying the measurements taken by the calibrated OP01-IT02 TWSTFT link [2].

For each set of repetitive measurements, closure measures are systematically performed. We demonstrate that the proposed method allows the characterization of OP-IT two-way satellite links in terms of earth stations differential delays with a combined uncertainty well below 2 ns.

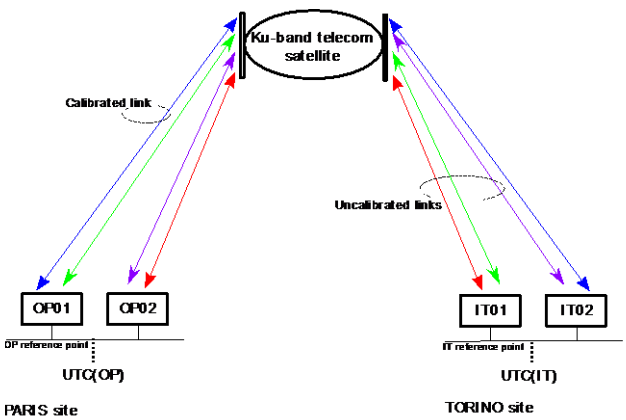


Fig. 1: configuration diagram of the various combinations of links between four stations which are fed, in pairs, by a common clock reference at each site, in Paris and Torino. The blue link (OP01-IT02) is the calibrated link, the remaining three links, in green (OP01-IT01), in violet (OP02-IT02) and in red (OP02-IT01) are those which are being characterized.

**Acknowledgment**

The authors thank the CCTF Working Group on TWSTFT for its support.

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# Design of Clock Laser with $10^{-16}$ Frequency Stability for Rapid Uncertainty Evaluation of Yb Lattice Clock

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For the uncertainty evaluation of the Yb lattice clock at KRISS (Korean Research Institute of Standards and Science) [1], which targets the frequency uncertainty of less than $10^{-17}$, a clock laser, whose stability is close to $10^{-16}$ at 1 s, is of great help in reducing the statistical uncertainty in reasonably short time. To attain this end, a cuboid-type 30-cm-long cavity [2] was adopted. This cavity is made of ULE, which has a zero-crossing temperature for the thermal expansion coefficient around room temperature. Two cavity mirrors are made of fused silica to reduce the thermal noise. ULE rings are optically contacted to fused silica mirrors to compensate the mirror deformation due to the thermal expansion difference [3]. By using mirror coating material with low thermal noise, the thermal noise limit is expected to be $4.3\times10^{-17}$. The vertical, longitudinal, transverse vibration sensitivity is calculated by finite element analysis to determine the optimum support position (Fig. 1). Calculated result for the vertical vibration sensitivities are shown in Fig. 2 as a function of longitudinal support position (d), transverse support position (s), and mirror offset from the mechanical axis.

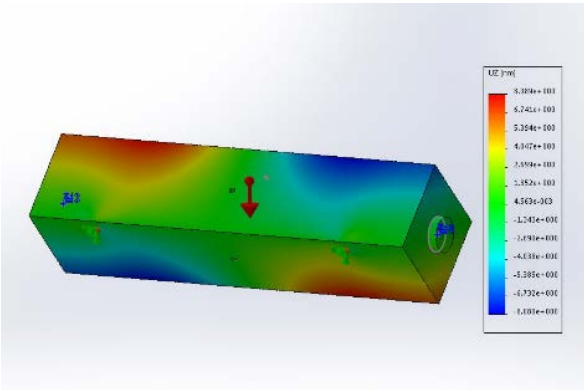

Fig. 1: Finite element analysis result of cavity deformation by vertical acceleration.

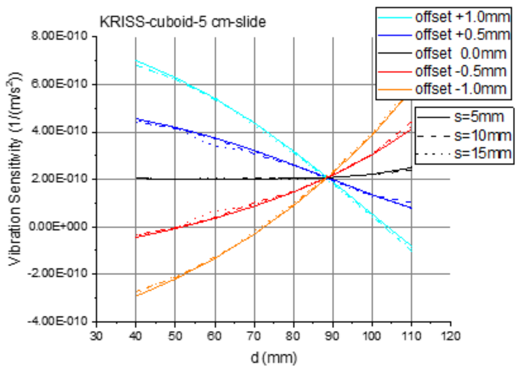


Fig. 2: Calculated vibration sensitivities as a function of longitudinal support position (d), transverse support position (s), and mirror offset from the mechanical axis.

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# Remote Time and Frequency Transfer Experiment Based on BeiDou Common View

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BeiDou navigation satellite system (BDS) is now offering an independent regional service for the Asia-Pacific region and it is going to offer global positioning service by 2020. And BDS will be another choice for remote precise time and frequency transfer.

Last year the zero-baseline common view test using BDS is done in BIRM and the result is better than 5ns. This year we have developed our own GPS/BD common view time and frequency transfer receiver and some remote time and frequency experiment were carried out using the receiver.

Our common view experiment is carried out both in BIRM-SIMT link and BIRM-NTSC link. In order to check our common view results, we took out TWSTFT experiment together when we made the common view experiment. Besides, since we have TTS-4 common view receiver in BIRM and TTS-5 common view receiver in SIMT, we compared the common view results of our receiver and TTS-4 and TTS-5 receiver. The experiment shows that our common view results agree with the TWSTFT results and the precision of our receiver is the same with that of TTS-4 and TTS-5 receiver. Also, we compared the common view results using GPS and BD which shows that the precision using BD is slightly lower than that of GPS.

# Mapping acoustic field distributions of VHF to SHF SAW transducers using a Scanning Electron Microscope

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Mapping the acoustic field distribution in surface acoustic wave devices is a useful indicator of energy confinement and the source of leakage, and hence of quality factor drop in resonators or, in the case of reflective delay lines, of poor reflected power when a fraction of the energy is not returned to the transducer. Additionally, unwanted transverse modes [1] might be generated when a large number of electrodes define the interdigitated transducer.

The traditional optical acoustic field mapping method [2] is limited to **out of plane** displacement mapping since all optical strategies are based on interferometric strategies in which the length of one arm of an interferometer is modified by the acoustic field. Despite the advantage of high frequency acoustic field mapping offered by fast photodiodes and the ability to extract the phase information in addition to the acoustic amplitude, the **inability to map shear wave** acoustic field distribution is a limitation of optical measurements.

A complementary approach is provided by mapping the electric field accompanied by the acoustic wave propagation on a piezoelectric substrate. Scanning Electron Microscopy (SEM) is a classical characterization method in which secondary electrons are recorded from a sample illuminated by a focused electron beam: the secondary electron signal intensity has been shown to be affected by the electrostatic field on a piezoelectric substrate and hence allow to map stationary acoustic fields in surface acoustic wave resonators [3] and bulk acoustic transducers [4]. Because of the limited bandwidth of the scintillator used to measure secondary electrons – in the 7 to 10 MHz bandwidth in the case of our Carl Zeiss Auriga SEM, travelling wave observation is not possible with an off-the-shelf instrument. Additional beam blanking to implement a stroboscopic approach [5]has been demonstrated to allow for time-resolved acoustic pulse propagation monitoring.

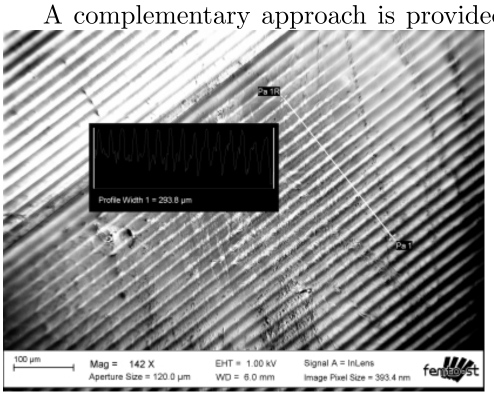


**Figure 1:** Acoustic field mapping on a lithium niobate delay line

In this work, we review some of the past SEM acoustic transducer field mapping activities, going back to 1978, and reproduce some of the measurements with more recent instruments. We investigate quartz resonators and lithium niobate delay lines, observing field distribution as a function of excitation frequency, for devices operating from 100 MHz to 2400 MHz.

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# Main Features of Space Rubidium Atomic Frequency Standard for BeiDou Satellites

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Wuhan Institute of Physics and Mathematics (WIPM), Chinese Academy of Sciences is one of the three China domestic suppliers of space borne rubidium atomic frequency standard (RAFS) for BeiDou navigation satellite system. WIPM started to develop space RAFS in late 1990's. The RAFS was space qualified in 2006, and started to be applied in BeiDou satellites in 2007.

The physics package of the space RAFS adopted separated filtering scheme. The most prominent feature of the physics package is that a new type of slotted tube cavity [1] is used, and both absorption and filter cells are located in the cavity, sharing one common heating oven. The cavity is of small size and a resonant mode close to $TE_{011}$. In the RAFS for BeiDou regional system, diameter of the two cells was taken as 14mm, and an argon gas rubidium spectral lamp was employed for pumping source. The lamp could work well in atmospheric and vacuum environments without changing operation parameters, and has been verified to be of operation lifetime longer than 20 years. The microwave chain included a 10MHz crystal oscillator, a ×9 RF multiplier, a ×76 SRD multiplier and a 5.3125MHz synthesizer. In the SRD multiplier the cavity in physics package was used for frequency selection. Analogue technique was used for all the electronic circuits to minimize the risk of element failure in space. To reduce thermal sensitivity of the RAFS, the whole frequency locking loop including physics package was put into a temperature controlled chamber. The operation parameters including the gas pressure, working temperature of the two cells and the lamp light intensity were optimized for realizing long term frequency stability. From 2007 to 2011, totally 10 space RAFS's developed by WIPM were equipped in BeiDou regional system. Their day frequency stabilities are within $2\sim5\times10^{-14}$ [2].

To meet the needs of BeiDou global system, improvement of the RAFS has been performed at WIPM. To enhance signal to noise ratio of the physics package, a cavity with larger size and better microwave distribution was used, cell diameter was increased to 20mm , and the argon gas lamp was substituted by a xenon gas one. Design of electronics remains nearly unchanged, but noise of the microwave chain was depressed by optimizing the circuit layout. A prototype of new generation space RAFS was built recently. Preliminary test showed that the day stability has reached $3\times10^{-15}$, comparable with the RAFS applied in GPS Block IIF satellites [3].

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# Recent Results of an Atomic Gravimeter Developing at KRISS

Sang-Bum Lee, Taeg Yong Kwon, Sang Eon Park, Myoung-Sun Heo, Hyun-Gue Hong, Chang Yong Park, Won-Kyu Lee, and Dai-Hyuk Yu

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We introduce recent results of an atomic gravimeter developing at KRISS. Fig.1a) shows atomic interferences between two ground states ($|F=1, m_f=0\rangle$, $|F=2, m_f=0\rangle$ of the free-falling $Rb^{87}$ atoms with the temperature of 3.4μK accumulated by two counter-propagating Raman lasers of Mach-Zehnder-Type configuration with π/2-π-π/2 (τ=60 μs) pulse sequence. By compensating g (gravitation acceleration)-induced Doppler shift by scanning of frequency sweeping rate α, we can find minimum fringe of excitation probability $N_2/N_T$ ($N_2$ is atom number of $|F=2, m_f=0\rangle$, $N_T$ is total atom number) which is independent of interrogation time T and correspond to $g = a/k_{eff,}$ where $k_{eff} = k_1+k_2$ ($k_1$ and $k_2$ are wave numbers for two counter-propagating beams). Fig.1b) shows g measured for 10 days from 20 to 30 November 2015. We will also discuss about limiting elements affecting the sensitivity of our gravimeter at this conference.

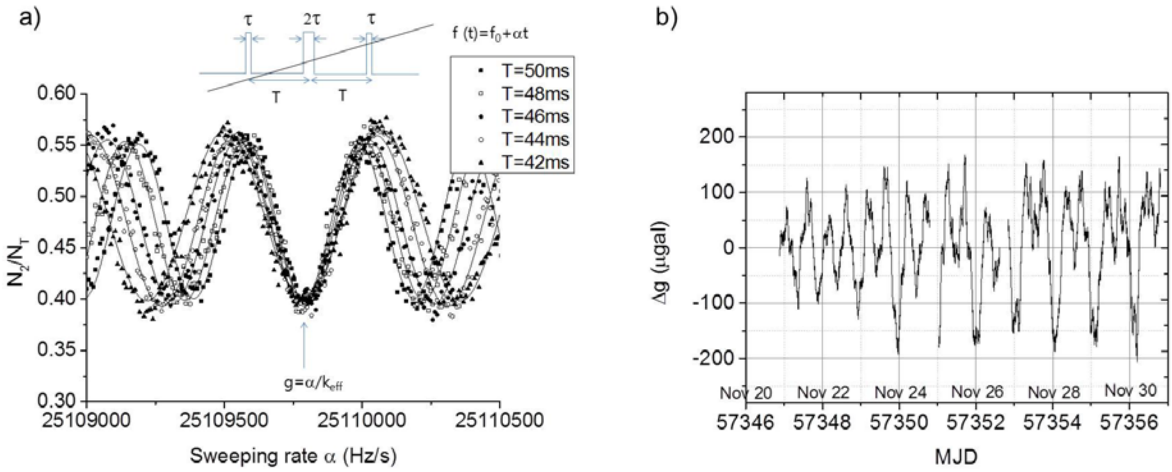


Figure 1 a) Interference signals generated by two counter-propagating Raman pulses of Mach-Zehnder-type configuration with π/2-π-π/2 pulse sequence. b) g measured from 20 to 30 November 2015.

# Non-destructive MEMS atomic vapor cells characterization by Raman spectroscopy and image analysis

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Among the different techniques used to fill microfabricated alkali vapor cell, the UV decomposition of rubidium azide ($RbN_3$) in metallic Rb and nitrogen ($N_2$) is a very promising approach for wafer-level fabrication. Here we report on the use of three innovative and non-destructive methods to characterize the decomposition yield and the buffer gas partial pressures ($N_2$ and Ar) of cells made with this technique: (1) Raman spectroscopy is used as a fast and quantitative method to estimate the $N_2$ pressure inside the cavity; (2) image analysis is used to quantify the amount of metallic Rb in the cell; (3) Raman is used to identify potential residues in the cavities after $RbN_3$ decomposition.

Our wafer-scale cell fabrication process is based on automated pipetting of small amounts of an aqueous $RbN_3$ solution into cavities etched in a silicon wafer, followed by hermetic sealing by anodic bonding of a glass cap under controlled argon (Ar) pressure. Metallic Rb and $N_2$ buffer gas are then created in situ by UV irradiation of the $RbN_3$ as described in more details in [1].

The amount of Rb and $N_2$ being stoichiometrically linked by the $RbN_3$ decomposition reaction, the pipetting and the UV irradiation must be well controlled in order to precisely adjust the $N_2$ partial pressure. We demonstrate that Raman spectroscopy, having the ability to measure diatomic gases, can be used as a fast and quantitative method to monitor the $N_2$ pressure in the cell. Thanks to an optimized calibration procedure, a detection limit of 5 mbar could be achieved. The measurements are found to be in very good agreement with pressures measured by CPT optical absorption spectroscopy which allow to independently measure the $N_2$ and Ar partial pressures.

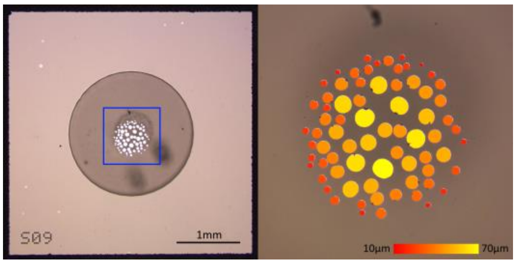

Fig. 1: MEMS atomic vapor cell filled with $RbN_3$ after UV decomposition (left). Metallic rubidium drops size extracted from image analysis inside the blue square region (right).

The Rb quantity being limited by the desired total buffer gas pressure, the lifetime of cells is more sensitive to Rb reactions with contaminants or with the cavity walls than other filling techniques. Fig. 1 shows an example of image analysis used to estimate the metallic Rb quantity present inside the atomic vapor cell and to monitor its evolution over time.

Potential $RbN_3$ residues are also analyzed by Raman after UV decomposition which allow to assess its full decomposition and detect remaining contaminants.

We will report on our latest measurements, showing the validation of those non-destructive characterization methods on a panel of microfabricated cells.

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# Recent advances in precision spectroscopy of ultracold atoms and ions

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New methods and approaches in precision spectroscopy of ultracold atoms and ions are discussed with an emphasis on contributions of Institute of Laser Physics SB RAS.

Presently, laser spectroscopy and fundamental metrology are among the most important and actively developed directions in modern physics. Frequency and time are the most precisely measured physical quantities, which, apart from practical applications (in navigation and information systems), play critical roles in tests of fundamental physical theories (such as QED, QCD, unification theories, and cosmology) [1,2]. Now, laser metrology is confronting the challenging task of creating an optical clock with fractional inaccuracy and instability at the level of $10^{-17}$ to $10^{-18}$. Indeed, considerable progress has already been achieved along this path for both ion-trap- [3] and atomic-lattice-based [4,5] clocks.

Work in this direction has stimulated the development of novel spectroscopic methods such as spectroscopy using quantum logic [6], magnetically induced spectroscopy [7], hyper-Ramsey spectroscopy [8], spectroscopy of "synthetic" frequency [9] and others [10]. Part of these methods was developed in order to excite and detect strongly forbidden optical transitions. The other part fights with frequency shifts of various origins. In the present talk we will review both parts with a special emphasis on methods developed and studied in Institute of Laser Physics SB RAS, Novosibirsk. The history and present status of experimental works devoted to the optical frequency standards will be discussed.

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# Experimental procedure to design stressed HBAR devices when the third-order elastic constants are not known

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Past papers at the EFTF conferences have focused on vibration sensitivity of High-overtone Bulk Acoustic Resonators (HBAR). Initial works have focused on the experimental result on HBAR with quartz or sapphire substrates [1] which present few $10^{-11}$/g sensitivity. Further investigations focus on the implementation of theoretical aspects on modeling tools. These works were validated by comparison between the results of design and experimentation [2]. The agreement is around 50%. Third-order elastic constants are mandatory requirements to compute stress sensitivity of HBAR. Thereby, most materials are not suitable to design low vibration sensitivity HBAR oscillator or pressure sensor. This work will present a new way to design such components when third-order elastic constants are not known. This approach is based on experimental measurements of stress sensitivity coefficients of HBAR. We use $LiNbO_3$ (YX*l*)/163 piezoelectric layer on $LiTaO_3$ Z-cut substrate as example of this approach.

Vibration sensitivity of HBAR oscillators are measured for different package configurations, including hinges in two axis and resonator orientations. These configurations allow the computation of the stress sensitivity coefficients of HBAR. For instance, Fig.1 shows the PSD results provided by one oscillator exhibiting a sensitivity of $4.5\times10^{-11}$/g. The six stress sensitivity coefficients of this specific configuration of HBAR have been computed. Hence, here, ${}^{s}\alpha_{mn}$ are $-2.9\times10^{-12}$/Pa, $4.3\times10^{-10}$/Pa and $9.4\times10^{-11}$/Pa for the first three. The accuracy of the coefficient estimate with respect to the experimental set-up will be presented. Combined with the distinguishing features of HBAR resonator such as *Q.f* product and temperature coefficient of frequency [3], a complete oscillator design optimization can be done thanks to these six stress sensitivity coefficients. Similarly, it is possible to design a pressure sensor although the involved nonlinear elastic constants have not been determined yet.

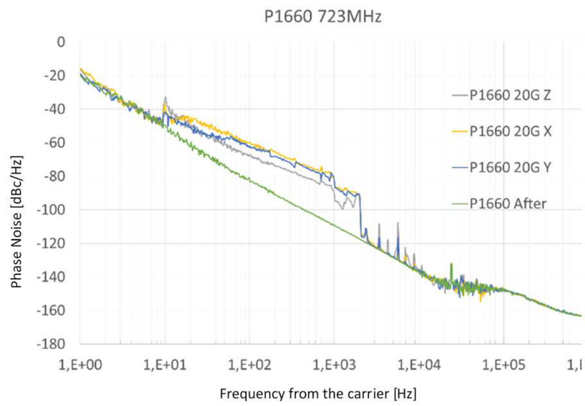


Fig. 1: Experimental phase noise density of an HBAR oscillator under vibration.

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# Absolute frequency measurement of the $^{173}$Yb clock transition via a 642-km fiber link

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In latest years, optical fiber links fully revealed their potential for remote clocks comparisons at unprecedented levels of accuracy [1]. Their exploitation in other research fields is envisaged as well, since it can push the current measurement limits forward, allowing the search for new physics. Nevertheless, frequency dissemination to non-metrological users requires to address specific technical issues and is currently limited to sporadic cases.

In Italy, a 642-km long coherent optical fiber link disseminates a Cs primary frequency standard to some of the most important research facilities in Italy [2]. Among these, is the European Laboratory for Non-Linear Spectroscopy (LENS) in Florence, where fiber-based dissemination significantly improves the precision of the previously available frequency standard, which was based on a GPS-disciplined Rb clock.

We exploit this facility for high-precision spectroscopy of an ultracold gas of $^{173}$Yb that is used for quantum simulations [3,4]. The coherent control on the atom electronic and nuclear degrees of freedom allows the investigation of fundamental effects which cannot be studied in their original physical context. On the other hand, long-term interrogation of the forbidden $^1S_0$-$^3P_0$ atomic transition is required for hours or even days, creating the need for manipulation lasers with narrow linewidth and exceptional long-term stability. The fiber-based dissemination of an optical frequency traced to the SI answers to this need, enabling long-term, SI-traceable spectroscopy of the clock transition of $^{173}$Yb.

We demonstrate the coherent optical link as a tool for high-precision spectroscopy, at a level which cannot be obtained with standard techniques. We also report an improvement of two orders of magnitude in the accuracy of the clock transition frequency reported in literature. At the conference we will report on the first results we obtained and on the future developments.

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# Relativistic Effect Correction for Clock Transport

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NICT established the second UTC generation station at Kobe and carried out the first calibration of the GPS link between Koganei and Kobe by using GPS, TWSTFT and Clock Transport (CT) in 2014. We presented the result of the calibration in last EFTF 2015 [1]. The obtained differential correction of GPS link by GPS, TWSTFT and CT were 102.5, 102.1 and 104.9 ns respectively. The results of GPS and TWSTFT agreed well. However, the CT result showed a discrepancy of 2 ns. At last EFTF, we concluded that the reason of this discrepancy is the uncertainty of the CT technique. This time, we applied the relativistic effect correction for CT and we confirmed a good agreement of the results obtained by their three techniques.

CT in a rotating reference frame is defined in Recommendation ITU-R [2]. When a clock is transported from a point A to a point B, the coordinate time accumulated during transport can be written as,

$$dt = \int_A^B ds\left[1 + \frac{\Delta U(\vec{r})}{c^2} + \frac{V^2}{2c^2}\right] + \frac{2\omega}{c^2}A_E \qquad (1)$$

where $dt$ is the elapsed coordinate time, $\int ds$ is increment of proper time accumulated on the portable clock, $\Delta U$ is the gravitational potential difference between the location of the clock and the geoid, $V$ is the ground speed of the clock, $c$ is the speed of light, $\omega$ is the angular velocity of rotation of the Earth, $A_E$ represents the equatorial projection of the area swept out during the transport of clock along its path [2], [3]. The first, second and third term in (1) express the gravitational redshift, the second-order Doppler shift, and the Sagnac effect, respectively. The equation 1 can be re-written as,

$$dt = \int_A^B ds\left[\frac{(9.780+0.052\sin^2\varphi)h}{c^2} + \frac{V^2}{2c^2}\right] + \int_A^B d\lambda\frac{2\omega\pi a_1^2\cos^2\varphi}{c^2} \qquad (2)$$

where $\varphi$ is geographical latitude, $h$ is distance above sea level, $\lambda$ is longitude, $a_1$ is equatorial radius of the Earth.

In this study, we calculated the relativistic effect by using driving route information (longitude, latitude, altitude) during the CT and the following assumption. The portable clock was transported by a van, the distance between Koganei and Kobe was about 600 km, the total elapsed time was about 8 hours, and the average drive speed was about 65 km/h. Figure 1 shows the calculated relativistic time gains for the portable clock for each of the contributing effects. The total relativistic time gains/losses by the transports from Koganei to Kobe, and from Kobe to Koganei were -1.4 and 2.8 ns respectively. We applied these values for the clock transport data. Finally, we obtained the differential correction of GPS link by CT was 102.3 ns. This result agreed with GPS and TWSTFT results with in 1 ns. This result suggests that CT still can be used for the remote calibration.

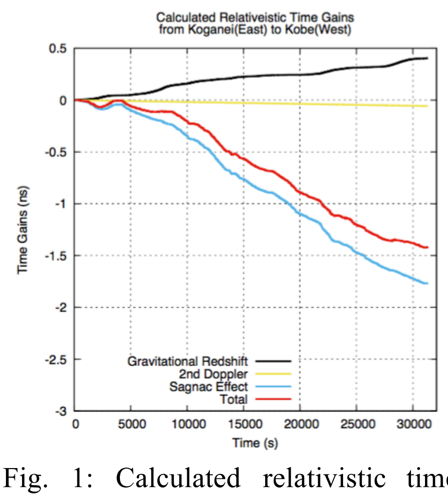


Fig. 1: Calculated relativistic time gains/losses for the portable clock for each of the contributing effects.

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# High Performance Miniature Integrated OCXO Solution

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Traditional OCXO devices have been around for many years offering frequency stabilities superior to those of smaller, lower power TCXO devices. In today’s world where size constraints and power conscious systems require exacting performance, this paper presents a unique solution that addresses these challenges. Based upon a TCOCXO topology [1], the single chip (ASIC) solution described requires only a crystal and optional capacitors to meet frequency versus temperature stabilities down to ±2ppb over -40/85ºC with an oven size of only 5x3.2 mm.

Designed as a flexible building block, the ASIC contains all of the necessary blocks for a complete solution. All the parameters needed to configure the design, both to match the thermal characteristics of the oven and package, through to setting the oven for the individual xtal requirements are stored in non-volatile memory. Multiple on chip heaters remove the need for discrete heating transistors and have the added benefits of much closer matching for even heat generation. Heating power for both 3.3Vand 5V applications is limited to about 3W.

The temperature is sensed from either an integrated ASIC PN junction, an NTC thermistor, or if required a combination of both. As shown in Fig1, the “error” signal from the proportional thermal control loop feeds an input into Chebychev polynomial generators that are set with programmable coefficients, unique for each device. The resultant summed output is used to control the oscillator, providing a 3rd order temperature compensation to minimize residual frequency errors from temperature excursions.

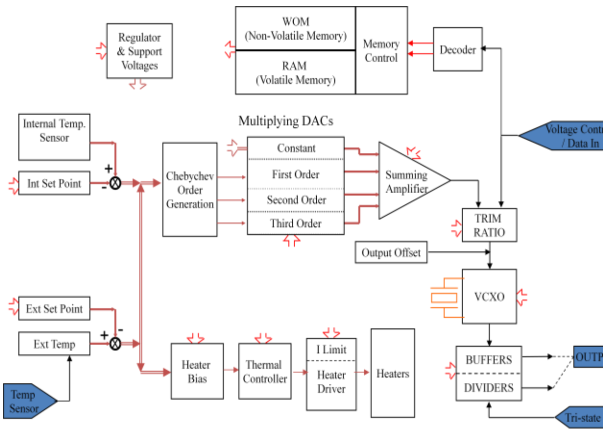


Fig. 1: Internal block diagram of ASIC, showing key features; heating control loop and temperature compensation.

The paper explores the options using the ASIC’s internal temp sensor, external sensor or mixed sensor arrangement for controlling the oven temperature and the temperature compensation, each with their own merits. Construction of the OCXO packaging, along with attention to assembly is key to ensuring that the power consumption is optimized and environmental effects are minimised.

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# Development of an ultra-stable frequency transfer in a commercial fiber-optic WDM-network

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To fully benefit from the advances in new optical ultra-stable oscillators, there must be an effective technique to distribute and transfer the optical frequency from the suppliers to the users. Best performance so far is undisputedly the techniques using a single bi-directional fiber connection, with customized bi-directional optical amplifiers. Some of the limitations of using this technique is the rental cost of dedicated fibers, or the availability of WDM-channels in networks accepting the frequent add-drop and specialized amplification or regeneration.

As a complementary technique, with less restricted performance requirement on frequency stability but with the impassable obligation to follow the deployed structure of telecom networks, an ultra-stable duplex-fiber frequency transfer is investigated. The frequency dissemination using this technique may then be applied at available wavelength channels in the operational communication networks, at low or no cost depending on the network operator. The current experimental network connects the Photonics research lab at Chalmers University of Technology in Gothenburg with the Ultra stable lasers and combs at the Swedish NMI SP Technical Research Institute of Sweden in Borås. The two-way fiber length is about 120 km and implemented in SUNET (Swedish University Network). The aim of the project is to evaluate the signal quality when sending a stable optical frequency utilizing a dedicated channel in a DWDM (Dense Wavelength Division Multiplexing) system fiber pair and in the future be able to multicast frequency in the network. The experiment uses the existing unidirectional amplifiers in the network and the wavelength in use is 1542.14 nm. This paper presents the most recent results of the frequency transfer and discusses the future plans for the fiber connection. If proven successfully, the long-term objective is to establish a distribution network for optical frequency references in Sweden.

The establishment and early results of the non-stabilized link has been previously presented[1]. The continuous evaluation and improvement will be aim at finding relevant performance specifications for a connection using this technique, and the available measurement data and analysis.

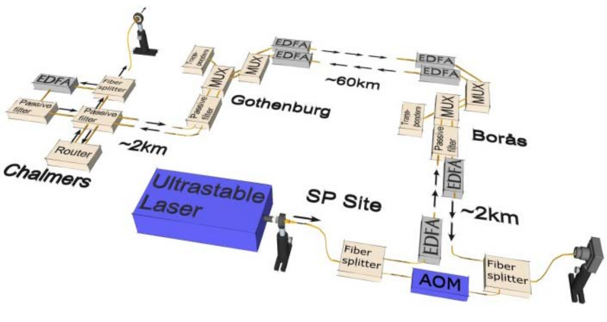


**Figure 1.** Schematic illustration of the experimental setup and the fiber connection between SP and Chalmers.

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# All Fiber coupled Ion Trap for Metrology

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We present an ion trap system with integrated optics for delivering laser radiation to single trapped ions and to collect their fluorescence. Utilizing this compact system we develop a low volume (< few liters), low power (<100W), portable atomic clock based on trapped calcium ions.

The system uses a radio frequency endcap trap with integrated fibers for fluorescence collection; the small trapping structure allows capturing ~6% of the solid angle. Pigtailed fibers are employed to deliver laser radiation for laser cooling and state detection. The resulting system is compact and rugged with no bulk optics and windows, thus providing precise control of the local environmental conditions.

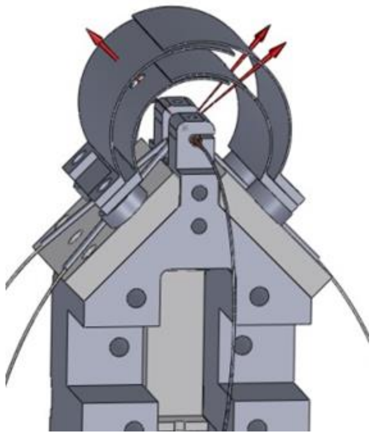

Fig. 1: Endcap ion trap with integrated fiber optics for fluorescence detection and laser light delivery.

We are currently developing an all-fiber laser system to provide all wavelengths for generating, cooling, repumping and interrogation calcium ions. The system is based on fiber coupled DFB and DBR laser diodes with fiber optical elements for switching, tuning and stabilizing the lasers.

# A cryogenic lattice clock at PTB

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We report on the implementation of a cryogenic optical lattice clock based on the $^1S_0 - {}^3P_0$ transition of $^{87}$Sr at PTB. While the atomic response to the blackbody radiation (BBR) field experienced by the atoms has been well characterized [1], our existing lattice clock is now limited to a total systematic uncertainty of $2 \times 10^{-17}$ [2] by our knowledge of the effective BBR field itself. Several groups [3-5] have already demonstrated approaches to control the BBR-induced frequency shifts to the level of few parts in $10^{18}$ and below, near room temperature or at cryogenic temperatures.

The lattice clock at PTB is successively being upgraded to a fully cryogenic lattice clock. In a first step, we have implemented a cryogenic environment into which the atoms are transported for interrogation. This has allowed us to achieve similar control of the BBR-induced frequency shifts and is expected to enable a total systematic uncertainty below $1 \times 10^{-17}$. A subsequent upgrade to a new physics package will remove the need for transporting the atoms and provide generally improved control of systematic effects to enable operation of the lattice clock at systematic uncertainties of few parts in $10^{18}$ and better.

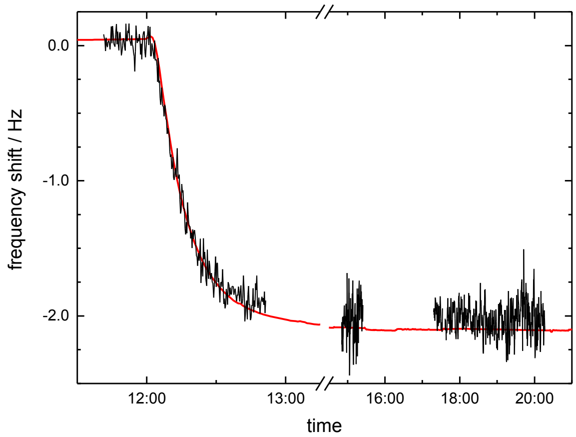


Fig. 1: Suppression of the BBR-induced frequency shift when the cryogenic environment of the lattice clock is cooled from room temperature to T = 86 K, showing recorded frequency differences from an interleaved self-comparison between the cryogenic environment and a reference outside (black), and expected shift derived from the measured temperatures (red). The observed residual frequency shifts at cryogenic temperatures are caused by the modification of the BBR radiation field at the reference position due to the cryogenic environment and are currently being investigated.

This work is supported by QUEST, by DFG within CRC 1128 (geo-Q) and RTG 1729, and by EMRP within ITOC and QESOCAS. The EMRP is jointly funded by the EMRP-participating countries within EURAMET and the European Union.

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# Improved uncertainty evaluations of the $^{171}Yb^+$ single-ion optical clocks of PTB

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$^{171}Yb^+$ provides two reference transitions that are adequate for the realization of an optical frequency standard: the $^2S_{1/2}(F=0)\rightarrow{}^2D_{3/2}(F=2)$ electric quadrupole (E2) transition at 436 nm and the $^2S_{1/2}(F=0)\rightarrow{}^2F_{7/2}(F=3)$ electric octupole (E3) transition at 467 nm [1,2]. The significantly higher sensitivity of the E2 transition to electric and magnetic fields permits diagnosis of field induced shifts of the E3 transition frequency on a magnified scale.

We report on a comparison of two independently operating $^{171}Yb^+$ single-ion clocks that use the E2 transition as the reference. The two systems employ very different ion trap geometries and control software, however, they show an agreement well below $10^{-16}$. Due to its significantly smaller sensitivity to external fields, an about tenfold improved agreement can be expected, if the E3 transition frequency is realized in both traps. By changing to the E3 transition frequency for one of the two systems, we also measured the frequency ratio of the E3 and E2 transition with an uncertainty a factor 2 smaller than that of a previous measurement [3]. Our total uncertainty of $1.4\times10^{-16}$ is essentially given by the uncertainty of the E2 blackbody radiation shift, which is in turn dominated by the differential polarizability of the E2 transition.

Although frequency shifts of the E3 transition related with quasi-static external fields can be investigated using the E2 transition, the excitation of the strongly forbidden E3 transition requires particularly high probe laser intensity, which in turn introduces a significant light shift via non-resonant coupling to higher lying levels. To avoid this frequency shift, over the last years implementations of Ramsey's method of separated oscillatory fields were proposed that rely on coherent composite pulse sequences substituting the standard $\pi/2$ drive pulses [4-6]. We present a conceptually different approach based on the incoherent combination of Ramsey interrogations leading to a universal pulse-defect immunity.

In this context we also discuss how heating of the ion's motion can degrade the cancellation of the light shift. Starting from a numerical analysis of the effect and an experimental investigation we demonstrate an approach to remedy the effects of motional heating.

S.K. acknowledges the DAAD (German Academic Exchange Service) for financial support.

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# Frequency ratio of a $^{171}Yb^+$ single ion clock and a $^{87}Sr$ lattice clock with $2 \times 10^{-17}$ uncertainty

Nils Huntemann[1], Sören Dörscher[1], Ali Al-Masoudi[1], Stephan Falke[1,*], Nathan Lemke[1], Sebastian Häfner[1], Christian Grebing[1], Burghard Lipphardt[1], Christian Sanner[1], Christian Tamm[1], Uwe Sterr[1], Christian Lisdat[1], Ekkehard Peik[1]

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We report on a direct comparison of two very different optical clocks. One is based on the $^2S_{1/2} - {}^2F_{7/2}$ electric octupole (E3) transition of a single $^{171}Yb^+$ ion stored in a radio-frequency Paul trap and the other clock realizes the $^1S_0 - {}^3P_0$ transition of many $^{87}Sr$ atoms confined in an optical lattice near the magic wavelength. The lattice clock achieves frequency instabilities smaller than $2 \times 10^{-16}/(\tau / s)^{1/2}$ [1] and a total systematic uncertainty of $2 \times 10^{-17}$ [2], while the ion clock has an estimated systematic uncertainty of $3 \times 10^{-18}$ and its instability limits the observed instability of the frequency ratio to $4.4 \times 10^{-15} / (\tau / s)^{1/2}$ as depicted in Fig.1.

More than eighty hours of acquired data result in a statistical uncertainty of $1.3 \times 10^{-17}$, and yield the frequency ratio of the two clocks with a total fractional uncertainty of $2.4 \times 10^{-17}$. This is the smallest uncertainty achieved for clocks of different type to date and significantly improves the knowledge of the ratio of these two secondary representations of the second. In particular, the determined ratio enables consistency tests in other laboratories developing the same combination of optical clocks, which can indirectly prove the agreement of independently built optical clocks.

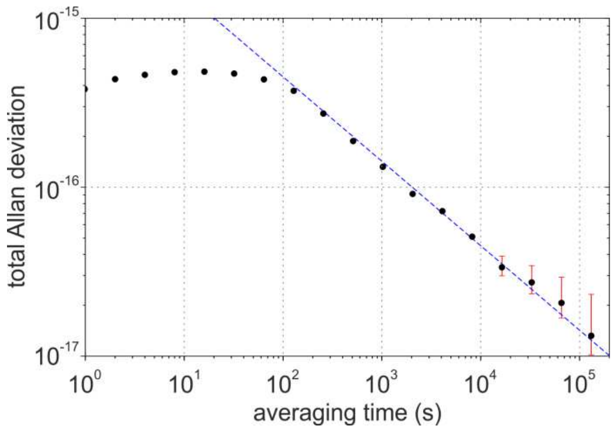


Fig. 1: Total Allan deviation of the optical clocks' frequency ratio as a function of averaging time. The dashed line indicates an instability of $4.4 \times 10^{-15} / (\tau / s)^{1/2}$.

The large sensitivity of the E3 transition frequency to the fine structure constant $\alpha$ makes the experiment suitable for a search for temporal variations of $\alpha$. With data from this recent measurement and a similar one performed two-and-a-half years earlier, we can provide the most stringent limit on a potential linear drift $\dot{\alpha}/\alpha$ from laboratory experiments.

This work is supported by QUEST, DFG within CRC 1128 (geo-Q) and RTG 1729, and EMRP within ionclock, ITOC and QESOCAS. The EMRP is jointly funded by the EMRP-participating countries within EURAMET and the European Union.

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# PTB's Transportable Strontium Lattice Clock

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Optical lattice clocks have currently reached remarkable performances that exceed the stability and uncertainty of the Cs fountain clocks. In particular optical lattice clocks based on $^{87}$Sr hold the record for accuracy and stability [1, 2]. The scientific community is working on a possible redefinition of the second based on this kind of clock [4], leading to the need of clock comparisons in the optical regime that cannot be achieved with satellite links. Furthermore, applications of such a good frequency reference include among others chronometric leveling-based geodesy with a precision in the order of centimeters [3].

A transportable clock at this level of accuracy enables such applications. Especially chronometric leveling strongly benefits from the ability to operate optical clocks at remote locations, which are interesting for geodesy.

Here we present the progress on our transportable lattice clock based on the fermionic $^{87}$Sr. To characterize the system, we have performed a series of comparison measurements (Fig. 1) of the transportable clock to our stationary strontium clock at PTB [3]. We measured the Stark-shift-cancellation wavelength for the transportable clock and investigated the uncertainty budget of the system at the low $10^{-16}$ level. We will also present the results of the first transportation tests of the system as a whole.

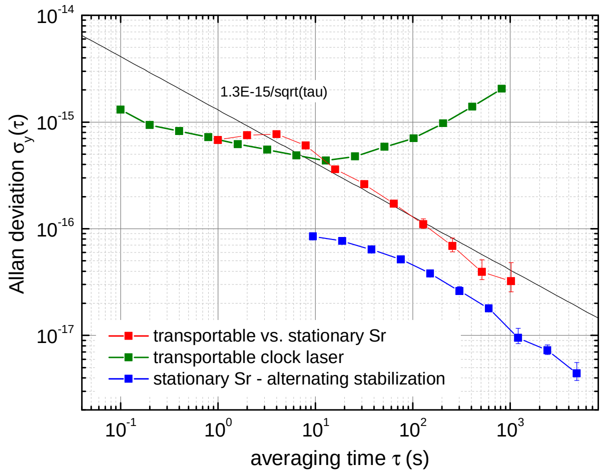


Fig. 1: Allan deviation for the comparison measurement between the two strontium lattice clocks at PTB. We reach an instability of $3 \times 10^{-17}$ after 1000 s of averaging. The stability is limited by the instability of the transportable clock laser.

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# $S_0$ Lamb wave resonators for in-liquid sensing: promising alternative to shear bulk acoustic wave devices

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The thin film electroacoustic (TEA) technology has gained considerable attention in the sensors field during the last decade. TEA sensors offer resolutions comparable and sometimes even better than their bulk crystal counterparts, while providing easier integration and compact sizes. In particular TEA sensors for in-liquid operation, employing the shear mode thin film bulk acoustic wave resonators (FBAR), have recently been developed in view of biosensors applications. For high performance shear mode operation these devices need piezoelectric deposition with tilted grains, which is still facing challenges in view of uniformity and large scale applicability. On the other hand, within the TEA sensors, Lamb wave resonators employing the $S_0$ mode ($S_0$-LWR) have demonstrated great potential for gravimetric sensors and suitability for in-liquid operation with the advantage of using commercial *c*-oriented AlN piezoelectric technology. However, their in-liquid sensing mechanisms and performance have not been properly described yet, neither compared to their FBAR counterparts.

Here we present extensive theoretical and experimental studies on the $S_0$-LWR (Fig. 1a) in-liquid behavior and compare them to the well-studied FBARs in their solidly mounted modality (SMR) (Fig. 1b). Both devices employ piezoelectric AlN and operate at 900 MHz frequency. Finite element analysis shows that $S_0$-LWR sensitivity is linearly dependent on the square root of the density viscosity product ($\rho{\cdot}\eta$), as that of classical shear mode bulk acoustic wave devices. However, for a given resonant frequency, they are more sensitive to $\rho$ than to $\eta$ due to their particular energy coupling to the liquid. Additionally, if their membrane bottom surface is not electrically isolated, they are also sensitive to variations of the dielectric permittivity ($\varepsilon$), which opens possibilities of dual quantity sensors integration.

To experimentally verify the theoretical model we simulated both devices considering ethylene glycol-water mixtures with varying $\rho{\cdot}\eta$ and $\varepsilon$, and subsequently performed experimental measurements with the same mixtures. Excellent agreement between our theoretical model and the experiments is demonstrated for both devices (Fig. 1c). $S_0$-LWRs demonstrate performance comparable to that of commonly used SMR, with slightly improved sensitivity. If a bottom metallic layer is not used for the $S_0$-LWR, the frequency shifts induced by $\varepsilon$ variations are superimposed to those induced by $\rho{\cdot}\eta$ variations. It is noted that decreasing $\varepsilon$ causes positive shifts of the resonant frequency.

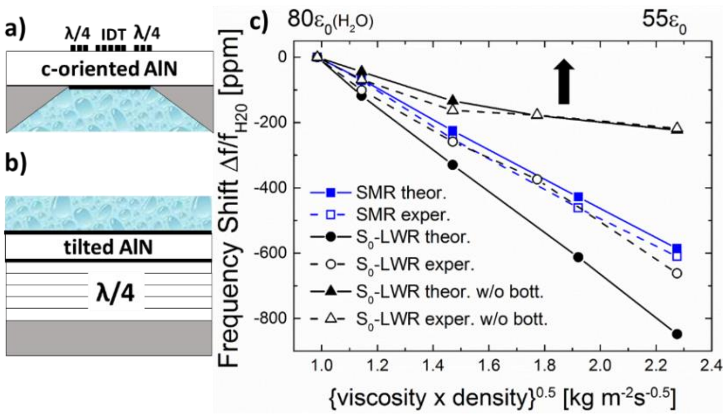


Fig. 1: $S_0$-LWR (a) and SMR (b) in-liquid measurements setup and their theoretical and experimental sensitivities to squared product of $\rho{\cdot}\eta$ and $\varepsilon$ of ethylene glycol-water mixtures (c).

# Sensitivity to a Variation of $m_e/m_p$ from Splittings between $^{12}C_2HD$ Reference Frequencies

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Molecular transitions were test grounds for searching a possible variation of the electron-to-proton mass ratio [1]. Degenerate molecular energy levels have splittings with an enhanced sensitivity to a variation of μ. A similar enhancement was demonstrated for pairs of near resonant transitions. They arise in the rovibrational spectra from the cancellation of effective rotational intervals with frequency shifts due to the vibrational band origin, the isotope effect or the rotation-vibration interactions. The terms competing to this degeneracy have different sensitivities to a variation of μ that enhances the sensitivity coefficient of the frequency splitting. The measurement of a temporal drift of small frequency splittings against Cs clock can probe unambiguously a possible variation of μ that have an enhanced contribution to this drift comparing to those from α, $g_{Cs}$. Some systematic frequency shifts may lead to a smaller uncertainty of the frequency difference than that of the frequency of a transition.

Absolute measurements of $^{12}C_2H_2$ $v_1+v_3$, $^{13}C_2H_2$ $v_1+v_3$ and $^{12}C_2HD$ $2v_1$ overtone bands lines between 193-198 THz were based on a laser source locked to saturated absorption lines by electro-optic phase-modulation and Pound-Drever-Hall technique with fractional Allan variance of $\sim 10^{-12}$ at 1 s and reproducibility of ~1 kHz (see [2] and references therein). The sensitivities to a variation of μ of $^{12}C_2HD$ rovibrational transitions are calculated in this contribution. Molecular energy levels are modelled in the Born-Oppenheimer approximation with an effective Hamiltonian for $2v_1$, $(v_1+v_3+v_5)^{1e}$, $(v_1+v_2+2v_5)^{0,2e}$ levels. The diagonal terms account for rotation and centrifugal distortion, respectively for vibration and anharmonicity. Non-diagonal terms account for the rotational l-type interaction of $(v_1+v_2+2v_5)^{0,2e}$, the Fermi interaction of $2v_1$ and $(v_1+v_2+2v_5)^{0e}$ and the Coriolis interaction of $2v_1$ and $(v_1+v_3+v_5)^{1e}$. Molecular constants of this Hamiltonian are issued from fits of experimental data [3] and their sensitivity to a variation of μ is calculated. Pairs of transitions splitted by GHz-level frequency gaps with sensitivity coefficients in the range of $\pm 10^3$ are identified. Measurement of both transitions with the same experimental setup under strict control of systematic effects may allow deriving constraints to a variation of μ. For example, systematic frequency shifts with fractional uncertainties of $\sim 10^{-10}$ are estimated for the splitting between P(16) lines of $^{13}C_2H_2$ $v_1+v_3$ band and $^{12}C_2HD$ $2v_1$ band of 1.54 THz with a sensitivity coefficient of ~1.

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# Diffractive optics for a compact, cold-atom microwave clock

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Laser cooled atomic samples have resulted in profound advances in frequency metrology, however the technology is typically complex and bulky. In recent literature [1] we describe a micro-fabricated optical element that greatly facilitates miniaturisation of ultra-cold atom technology.

Portable devices should be feasible with accuracy vastly exceeding that of equivalent room-temperature technology, with a minimal footprint. These laser cooled samples are ideal for atomic clocks. Here we will discuss next generation diffractive optical elements (DOE) that have been optimised for implementation in cold atom apparatus. Furthermore, we will demonstrate our work towards building a robust, compact cold atom clock based on a Raman-Ramsey interrogation of the cold atomic sample.

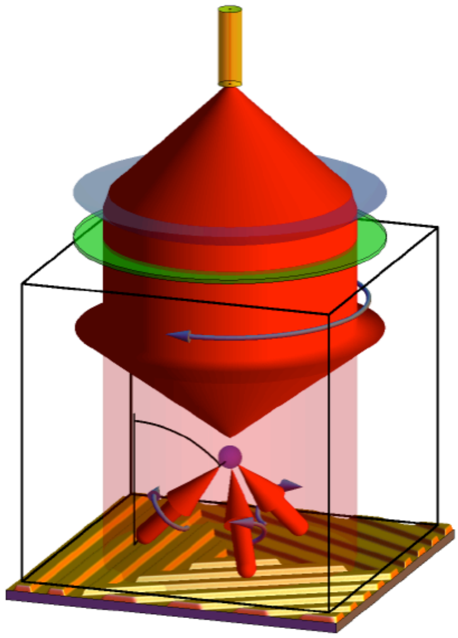

Fig. 1: Simplified laser cooling set-up with circularly polarised light incident upon a diffraction grating to generate the balanced radiation pressure required for laser cooling.

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# DFG comb showing quadratic scaling of the phase noise with frequency

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We characterize an Er:fiber laser frequency comb which is passively carrier envelope phase-stabilized via difference frequency generation at a wavelength of 1550 nm. A versatile method to measure the phase noise for a broad range of optical frequencies is demonstrated. Here, it is used to characterize our DFG comb over nearly an optical octave. With repetition-rate stabilization, a RF-reference oscillator limited line-width is achieved. A lock to a low-noise optical reference implemented by an external cavity diode laser locked to a high-finesse cavity shows out-of-loop line-widths of the comb at the Hz level. The phase noise measurements are in excellent agreement with the elastic tape model with a fix point at zero frequency.

Several methods for stabilizing the carrier-envelope offset, fceo have been demonstrated, but it is also possible to fundamentally remove fceo from the comb output using difference frequency generation (DFG) [1]. Broadening an Er:fiber comb, such that the DFG of the most separated spectral components results at 1550 nm, allows for a technologically elegant solution [2].

We characterise the comb at a wide range of optical frequencies by transferring the properties of a comb line to a cw external cavity diode laser. The cw laser noise properties are then measured by tracking the delayed self-heterodyne beat note [3]. This relatively simple yet versatile characterization method is suitable for a broad range of optical frequencies and is used to characterize our DFG comb over nearly an optical octave.

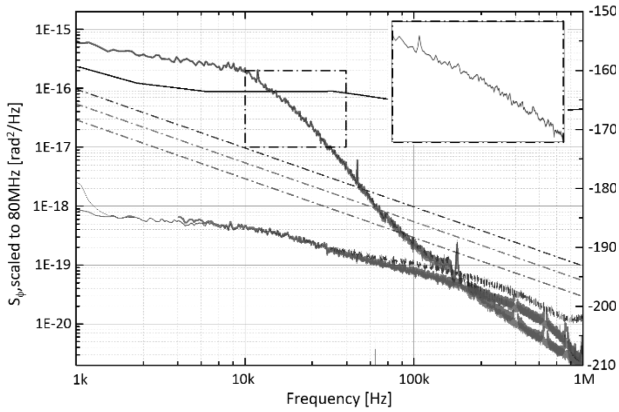


Fig. 1: Phase noise spectra scaled to frep=80 MHz carrier: The phase noise spectra are shown in two groups: upper group for the comb locked to an 800 MHz RF-reference with zoom (inset) and lower for the lock to the optical oscillator. The noise of the RF reference oscillator as well as the beta separation lines (dashed dotted) are shown for reference.

The noise spectra show a 1/f-dependence above 100 kHz following the free-running Er:fiber oscillator noise. The results in Fig.1 are the simultaneously measured noise spectra at 1557 nm (dark), 1162 nm (medium), and 852 nm (light gray) rescaled to a fixed carrier frequency of frep=80 MHz. The measured noise at the different wavelength outputs are correlated to within the detailed random noise structure (see inset) thus showing excellent agreement with the elastic tape model for a DFG comb with a fix point at zero frequency.

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# A magnesium optical lattice clock

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We report on the progress towards a highly-accurate optical lattice clock with bosonic $^{24}$Mg. Recently, we measured the frequency of the magnetically enhanced $^1S_0 - {}^3P_0$ clock transition at 458 nm to be 655 058 646 691(101) kHz and determined its magic wavelength of 468.46(21) nm. The quadratic Zeeman shift of the clock transition was found to be -206.6(2.0) MHz/$T^2$ [1]. All values are in agreement with previous calculations.

The maximum achievable lattice depth of these measurements was approximately 10 recoil energies (equivalent to $U_0$ = 20 μK), being limited by the available lattice laser power. According to Ref. [2], the corresponding width of the lattice ground state's energy band has an impact on the carrier transition linewidth in terms of a frequency shift and a broadening. For the above mentioned trap depth, the expected ground state band width is approximately 3 kHz, which agrees with our findings.

Having set up a new laser system for the generation of the magic wavelength lattice, we hence further increased the trap depth. We evaluate the systematic effects of our magnesium optical lattice clock and report on the progress towards an absolute frequency measurement of the $^1S_0 - {}^3P_0$ clock transition in $^{24}$Mg using the fiber link to Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig [3].

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# Atomic sources for gravitational wave detectors

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Atom interferometers in a differential mode were proposed as gravitational wave detectors in the sub Hz – 10 Hz regime in ground based setups [1] and frequency ranges comparable to LISA in space borne devices [2]. The sources supplying the atoms have to provide a high flux of ultra-cold atoms with a high stability of the position and the velocity of the center of the wave packet. Proposed ground based setups typically rely on the combination of alkali atoms which are widely used in precision experiments [3,4] and high order multiphoton transitions to avoid baselines between the atom interferometers exceeding few kilometers [1,5]. In a space borne device, longer baselines are possible implying a delay between the atom light interactions at both atom interferometers and consequently requiring extremely low beam splitter laser frequency noise. To mitigate this requirement, the manipulation of the optical clock transitions in earth alkali like atoms was proposed [6].

We performed a trade-off for several atomic species with optical clock transitions for a space borne setup aiming for a strain sensitivity of few $10^{-20}$ $Hz^{-1/2}$ for sub Hz frequencies [2]. Therein, we considered abundance, required lasers, the linewidth of the clock transition, and investigated quenching parameters for bosonic species. The flux for several temperature regimes was evaluated and residual expansion rates and sample sizes were estimated after a delta kick collimation [7,8]. Based on these parameters, the source-related error contributions were modelled.

In this contribution, we will discuss the evaluated parameters and present the results of the trade-off to come up with an appropriate atomic source concept.

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# Phase lock and laser characterization

# for the probing of trapped Ca+ ions

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Coherent population trapping allows to exploit multi-photon spectroscopy with a very high precision [1]. A cloud of trapped ions is an excellent sample to measure, for example, transition dipoles with an uncertainty inferior to $10^{-3}$, necessary to push forward today's best calculations [2].

Our ion of choice is Ca+, which is laser-cooled by two lasers at 397 nm and 866 nm, while the excitation of its electric quadrupole (clock) transition is made at 729 nm. We have developed and realized a narrow linewidth laser at this latter wavelength that attains a fractional frequency stability below $5.10^{-14}$ at one second. This optical wave at 729 nm is transported by a 150m long phase-noise cancelled fibre to the experimental set-up.

In order to phase-lock all involved laser sources, we make use of an offset-free commercial frequency comb [3]. In the final experimental configuration, the frequency comb is locked to the 729 nm-laser, while the 866nm and 794 nm (=2*397 nm) lasers are phase-locked to the frequency comb.

We have characterized all phase noise contributions, in order to evaluate the ultimate frequency stability we can attain. As the frequency comb is a novel equipment, a particular effort has been made to characterize its performances with respect to our stable laser and GPS. Measurements are ongoing and results will be reported at the conference.

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# Quantum Tests of the Universality of Free Fall

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Modern physics stands on the two pillars that are quantum field theory, describing matter at the most microscopic scales, and Einstein's general relativity theory which conveys our understanding of gravity over the largest distances across the universe. While both theories have delivered invaluable contributions at their respective scales, no theory unifying all four fundamental interactions and consistent over all energy scales exists to date. Nevertheless, certain theories of "quantum gravity" enable a reconciliation of quantum field theory and general relativity through violations of the universality of free-fall (UFF), one of the components of Einstein's equivalence principle together with Lorentz invariance and local position invariance. As the foundation of general relativity, the UFF, the fact that all bodies at the same point in space time experience the same acceleration in a gravitational field independently of their composition, has been tested extensively, mostly with macroscopic test masses, with best accuracies up to a few parts in ten trillion [1, 2].

Matter wave interferometers represent a novel method for testing the UFF that differs fundamentally from experiments employing macroscopic test masses by using genuine quantum objects as test masses. We report on a quantum test of the UFF with a 100 ppb uncertainty using two different chemical elements, $^{39}$K and $^{87}$Rb [3] and recent improvements of the experiment aiming towards a ppb test including correlated noise suppression.

In the future, Very Long Baseline Atom Interferometers (VLBAI) reprensent a new class of matter wave sensors which extend the baseline from tens of centimeters to several meters, enabling free-fall times on the order of seconds. This not only opens the way for competition with state of the art superconducting gravimeters when operated as single species gravimeters but also aims at quantum tests of the UFF at levels comparable to the best classical tests and beyond. We present our strategies for the construction of such a VLBAI which include in particular the use of the alkaline-earth-like element ytterbium [4].

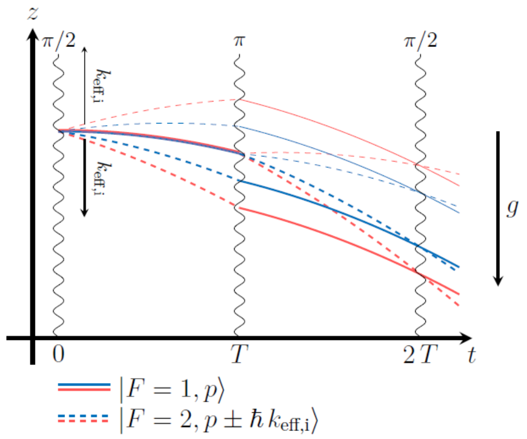


Fig. 1: Space-time diagram of a dual-species (Rb: blue lines, K: red lines) Mach-Zehnder matter wave interferometer based on stimulated Raman transitions in a constant gravitational field.

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# Light-Shift Coefficient in GPS Rubidium Clocks: Estimation Methods using Lamplight/Frequency Correlations

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Rubidium atomic frequency standards (RAFS) are a key technology for global navigation satellite systems (GNSS). However, their output frequency is affected by the light-shift effect [1], due to the optical-pumping light from the RAFS' rf-discharge lamp. As a consequence, lamplight intensity variations can induce RAFS output frequency variations [2], with lamp-light stability setting a lower bound to RAFS frequency stability (i.e., to the eventual navigation performance of the GNSS).

In order to uncover the effect of the lamp on the frequency, it is necessary to estimate the RAFS' on-orbit light-shift coefficient, LSC, defined operationally as the lamplight/frequency correlation, since one cannot simply adjust the lamplight's level and record a change in RAFS frequency as one might in the laboratory. Further, little is known regarding light-shift coefficients of GNSS-quality RAFS: their general magnitudes and signs; the variance in LSC among a population of GNSS RAFS; the stability of a RAFS' LSC over time.

The present work discusses two different methods for estimating the LSC of an on-orbit RAFS, validates the methodology using GPS Block IIR RAFS data, and presents some preliminary LSC generalities. We employ RAFS frequency data from the Information-Analytical Centre and downloaded GPS RAFS lamplight telemetry data.

The first method makes use of large observed frequency jumps that are induced by lamplight jumps; the second uses the linear correlation between deterministic frequency and lamplight variations (Fig. 1). The last method also allows better analysis of possible variations of the LSC over time, which we will discuss.

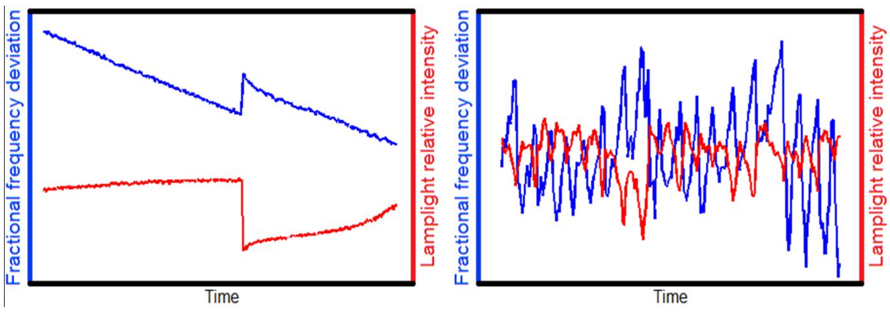


Figure 1: On the left, a correlated lamplight and frequency jump; on the right, an example of correlation between deterministic lamplight and frequency variations.

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# Hydrogen plasma simulation for atomic clock lifetime assessment

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Passive Hydrogen Masers are currently embarked onboard of Galileo constellation and are showing outstanding performances. However, given the lack of statistic over lifetime, parallel activities are ongoing for analyzing possible failure mechanisms and improve the robustness. On the base of ground experience and technology review, one of the most critical sub-system is represented by the hydrogen gas dissociator[1]. Based on ground observation of the quartz vessel aging processes, it was identified the need for a representative simulation model of the hydrogen plasma. After a review of the different available commercial software, COMSOL Multiphysics was selected for its ability to cope with different physics, allowing to investigate possible wear-out effects. A 2D axisymmetric model was created computing the ignition of the plasma until reaching a steady state. 8 species were considered, 4 neutral ($H_2, H, H(n=2), H(n=3), H(n=4)$) among which 3 excited stated and 3 ions ($H^+, H_2{}^+, H_3{}^+$) linked by 24 volume reactions and 12 surface reactions[2].

Results show that the shape of the plasma distribution does not change with the different input parameters such as gas pressure, antenna power or antenna frequency refuting the possibility of a multi-mode plasma, as differently happens with some alkali rf-discharge lamps (e.g. Rubidium). However the investigation of the ion flux clearly shows a preference direction: the ions mainly impact the quartz surface close to the antenna, confirming to be the sputtering one of the main aging effect on the quartz vessels. To the authors knowledge, this is the first time that CAE simulation is used for studying plasma related wear-out effects of atomic clocks. This approach can be actively used for dissociation optimization and rf-dissociator improvement.

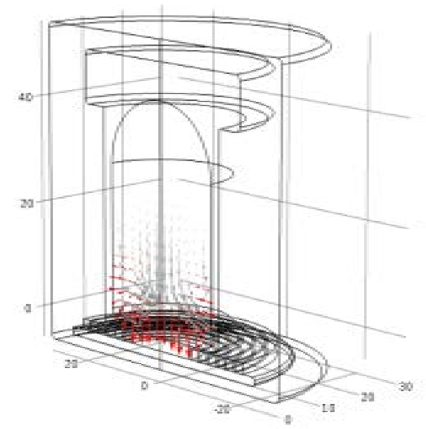

Fig. 1: $H_2{}^+$ total flux (red), electron total flux (gray) in steady state hydrogen plasma.

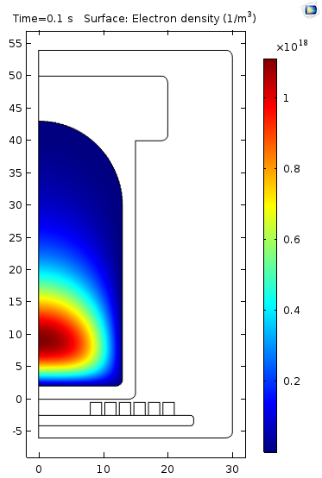


Fig. 2: Electron density in steady state hydrogen plasma

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**Generation of a time scale at ESOC**

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In April 2013, an activity for generating a time scale at ESOC using the three already available Active Hydrogen Masers was started. The scale is realised by steering to UTC one of the active hydrogen maser as signal source, whose frequency is steered via a commercial high resolution microphase stepper.

The monitoring is based on GPS Precise Point Positioning (PPP) results by comparing the ESOC time scale to existing UTC time scales, mainly UTC(PTB) and UTC(ESTC). Using the IGS Rapid orbit and clock products, the PPP-based time transfer results are obtained with ESA's state-of-the-art GNSS data processing software package NAPEOS.

For the testing phase, the steerings consider the time and frequency offset of the ESOC time scale against UTC(PTB) and are applied in a time-interval of 3 days within a fully automated process.

After the system finalisation tasks and the maintenance period in October 2015, the time scale has been kept within $\pm 5$ns with respect to both UTC(PTB) as well as UTC(ESTC) for a time period from 21/11/2015 to 21/12/2015.

Three proprietary software tools have been developed in LabView for processing the measurements of a Phase Comparator (PCO):

- The real-time monitoring tool can display ADEV / OADEV, as well as three-corner-hat at chosen intervals
- The post-processing tool adds the display of DVAR 3D-plots
- The clock files tool generates the daily and monthly files for the UTCr and the UTC respectively.

For the future, it is planned to enhance the time scale with additional clocks (eg. Cs clocks), to add redundancy to the steering and the post-processing of the data, as well as to put additional monitoring equipment for the phase and time offsets.

The time scale will be operationally used by the ESOC Navigation Office for the enhancement of their clock products, and by the ESOC Ground Systems Division for time transfer to the Deep Space Stations in Malargüe (Argentina), Cebreros (Spain) and New Norcia (Australia), improving the time synchronisation for the every time more demanding scientific missions.

# Remote optical and fountain clock comparison using broadband TWSTFT and GPS PPP

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At the European metrology institutes INRiM, LNE-SYRTE, NPL and PTB, various optical and caesium fountain clocks were running simultaneously for a direct remote comparison over 3 weeks via Two-Way Satellite Time and Frequency Transfer (TWSTFT) and Global Positioning System (GPS) frequency transfer. Two different secondary representations of the second, the electric octupole transition of single $^{171}Yb^{+}$ ions (operated at NPL and PTB) and the reference transition of $^{87}Sr$ atoms in an optical lattice (operated at LNE-SYRTE, NPL and PTB) were compared and additionally, the Cs fountain clocks at INRiM, LNE-SYRTE and PTB were operated at the same time for intercomparison and absolute optical frequency measurements. The optical clocks were operated with uptimes up to 90%.

To achieve lower instabilities than provided by the regularly operational TWSTFT technique, full 20 MChip/s modulation bandwidth links between all four institutes were employed. For GPS analysis the well-established Precise Point Positioning (PPP) and the recently developed integer PPP methods were used. The satellite links were continuously in operation, resulting in phase data for TWSTFT and GPS on a 1 s and a 30 s grid, respectively.

At each institute, a hydrogen maser was used as a common reference for the TWSTFT modems, the GPS receivers and the optical and Cs fountain frequency measurement, allowing the maser contributions to be cancelled out in the clock comparisons.

Both satellite-based techniques show instabilities of a few $10^{-16}$ at 1 day averaging time, enabling the comparison with a statistical uncertainty in that range. For calculating the remote clock-to-clock frequency ratios and the corresponding uncertainties, gap-tolerant weighted averaging with different weighting functions optimized for the suppression of noise and technical disturbances was employed.

Acknowledgement: This work was performed within the ITOC project as part of the European Metrological Research Programme EMRP. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

# Stress-Sensitivity of Wafer-Level Packaged SAW Delay Lines

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It is known that the future of MEMS and SAW sensors developed in laboratory highly depends on the stability and reliability of the electrical parameters after packaging. In this paper, we present the investigation of the influence of wafer-level packaging (WLP) on the stress-sensitivity of 100 and 200 MHz delay lines aimed to wireless sensing of stresses. The devices were fabricated on YX*l-/128°* cut of $LiNbO_3$ (LN). The most common wafer-bonding techniques used in RF MEMS are direct surface bonding, glass frit and metallic layer bonding, which result in a rigid contact between the wafers that minimizes the extensional stresses at the interface, close to the neutral fiber of the assembly. Since it coincides with the region of acoustic energy localization, such WLP results into poor stress sensitivity of the sensors. Conversely, softer bonding by polymers permits to keep significant stress levels near the wave-guiding surface while providing sufficient protection to the device. We investigated a new Wafer-Level Packaging achieving the assembly of two LN wafers by a thin layer of SU-8 polymer. The first wafer is the actual delay lines substrate and the second wafer realizes the function of protective cap. Contact pads are of located outside the capped region in order to support simple wires for electrical connections or antennas for wireless sensing.

The paper focuses on the comparison between theoretical and experimental phase sensitivity of packaged and raw configurations of the devices versus extensional and bending biases. The results of static bias tests performed on the devices are confronted to an acousto-elastic analysis performed on the base of available values of linear and nonlinear elastic constants [1] within the framework of mixed analytical/FEA studies and advanced simulation software for SAW devices.

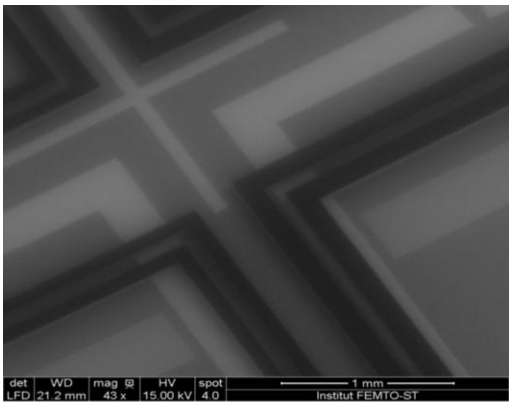


Fig. 1: Example of SU-8 pattern on top of SAW delay-line

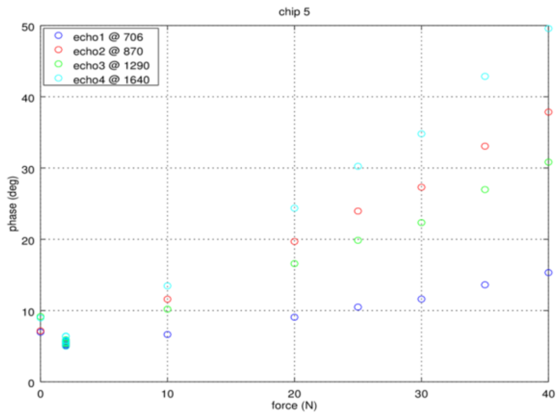


Fig. 2: Phase shift of a 200MHz packaged LN 128° delay line during a 3-points bending experiment.

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# Development of a high performance optical cesium beam clock for ground applications

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Cesium beam clocks are used as primary reference frequency and time sources for numerous applications (metrology, science, navigation, synchronization …). Commercial clocks are based on magnetic deflection of a thermal cesium beam. Such clocks provide a frequency stability of $\sigma_y(\tau) \leq 2.7\text{E-}11\ \tau^{-1/2}$ with a typical lifetime of 10 years, while improved stability performance at $\sigma_y(\tau) \leq 8.5\text{E-}12\ \tau^{-1/2}$ reduces the clock lifetime to 5 years.

By using laser sources at either the cesium D1 or D2 lines (894 nm or 852 nm), magnetic state selection of the cesium atomic beam can be advantageously replaced by optical pumping that strongly increases the useful atomic beam flux by two orders of magnitude. Several laboratory or industrial bread boarding experiments have demonstrated up to a ten-fold frequency stability improvement ($\sigma_y(\tau) \leq 3\text{E-}12\ \tau^{-1/2}$) with an operating temperature of the cesium oven compatible with a 10 years clock lifetime [1-4].

Thanks to the improvement of the laser diode module performance, reliability and lifetime, Oscilloquartz SA, Switzerland has started an industrial development of an optically-pumped cesium beam atomic clock for ground applications. The aim is to get a transportable clock fitting in a standard frame (19” width, 3U high), providing an output signal frequency stability of $\sigma_y(\tau) \leq 3\text{E-}12\ \tau^{-1/2}$ with a 10 years lifetime. The design of all components of the clock is achieved (cesium tube, optics, electronics and mechanics), all parts have been procured and all sub-systems are being assembled. Clock integration results will be presented at the conference together with frequency stability measurements and a signal-to-noise budget analysis.

This development is supported by the European Space Agency under the European GNSS Evolution Program (EGEP ID-90).

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# Progress on the CPT clock:
# Reduction of the main frequency noise sources

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Clocks based on coherent population trapping (CPT) [1] represent promising candidates for on-board space and industrial applications thanks to their simple scheme and high stability performance [2, 3].

Here, we report on the performance obtained with a laboratory compact CPT caesium clock. The CPT signal is observed on the Cs D1 line transmission, using a double Λ scheme and a Ramsey interrogation technique. A great deal of work has been done to investigate the two main frequency noise sources: the local oscillator frequency noise (Dick effect [4]) and the laser intensity noise. It led to a state-of-the art stability measurement at the level of $3.2\text{x}10^{-13}$ at 1 s [2]. Moreover it has been calculated that the stability could be improved by 30% just by optimizing the Ramsey interrogation and the detection time [5].

In order to reach the ultimate performance of our system, further investigations are carried on to improve the short-term stability. The Dick effect contributions are carefully addressed: 1) A better 100 MHz quartz oscillator is used for the frequency synthesis chain; 2) The frequency chain is being revised; 3) The optical phase lock loop (OPLL) of the two lasers has been optimized (Table 1).

We are also aiming to improve the signal-to-noise ratio by stabilizing the intensity of the lasers and normalizing the absorption signal by the laser power measured on the cell input, in order to compensate the noise added by the acousto-optic modulator (AOM) chopping the beam.

| **Frequency noise source** | | **Contribution $\sigma_y(1\text{ s})\,\text{x}10^{13}$** | |
|---|---|---|---|
| | | **2014** | **2016** |
| Dick effect | 100 MHz | 1.2 | 0.75 |
| | Frequency chain | 1.0 | (<1) |
| | OPLL | 2.1 | 1.75 |
| Laser intensity | | 1.9 | 1.5 |
| **Total** | | 3.2 | (<2.6) |

Table 1: *The main frequency noise sources and their stability contribution (expected numbers).*

The results of these studies will be presented at the conference.

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# Highly Dynamic Distance Measurement for GNSS using the Frequency Domain Distance Measurement, for Time and Frequency Transfer

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A new approach of distance measurement promises a very compact, robust, simple and fast application. The Frequency Domain Distance Measurement (FDDM, [1]) is hereby not only for absolute distance measurements, but for highly dynamic measurements as well. This system is capable of measuring static systems as well as highly dynamic systems with speeds > 10 km/sec, and velocity resolution < 1 cm/sec. The combination of FDDM and a balanced optical cross correlation promises time and frequency transfer between largest distances with stabilities better than optical clock performances, which can be used for future Global Navigation Satellite System (GNSS) scenarios.

Optical frequency combs for absolute distance measurements [2] can be done with multiple techniques like Modulation Sideband Technology for Absolute Ranging [3], dual-comb distance measurements and the here presented FDDM. The difference of the FDDM to the other types lies within the simple handling of an only repetition rate stabilized femtosecond-(fs-) laser and the data measurement below 2 GHz.

The FDDM requires a continuous pulse train generated by a fs-laser, which is overlapped with itself after propagated along a reference distance $d_{ref}$ and a target distance $D$. A schematic view of the setup and the measured effect is shown in Figure **1**a and Figure **1**b.

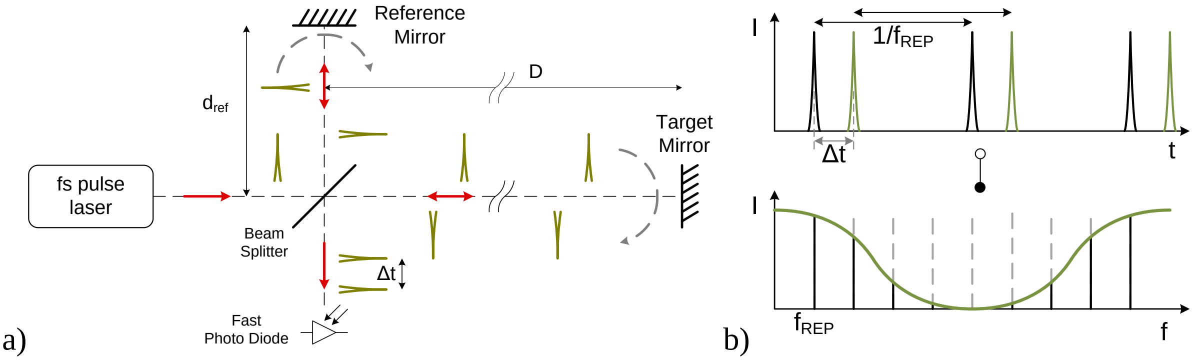


Figure 1: a) schematic measurement setup
b) influence of time offset to harmonics of the repetition rate

As indicated, a temporal offset between the incoming pulses correlates with an amplitude variation of the harmonics of the repetition rate. The modulation of the harmonic voltage can be described as [1]

$$U_m(\Delta t, U_{m,1}, U_{m,2}) = \left| \sqrt{U_{m,1}^2 + U_{m,2}^2 + 2U_{m,1}U_{m,2}\cos(m2\pi f_{REP}\Delta t)} \right|$$

Where - $U_{m,x}$ is the non-disturbed voltage of the $m^{th}$ harmonic of $d_{ref}$ (x=1)/ $D$ (x=2)
- $\Delta t$ is the time offset of the incoming pulses
- $f_{rep}$ is the repetition rate of the fs-laser

If the target is moving with $v_{target}$,(<< c, speed of light) the $m^{th}$ harmonic oscillates with the frequency

$$f_{U,m} = 2m \cdot \frac{v_{target}}{c} \cdot f_{REP}$$

By monitoring multiple harmonics the current position of the target can be clearly defined and the velocity can be determined with high resolution. This information can be used to calculate the Doppler shift between the two systems. A time and frequency transfer can then be implemented using the fs-laser in combination with a BOCC setup [4] in a satellite system with rapidly changing inter-satellite ranges.

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# Memory-efficient high-speed algorithm for multi-τ PDEV analysis

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The introduction and analysis of PVAR [1] provides improved white phase noise rejection over the MDEV. However, the existing formulas do not provide guidance for data decimation, such as available for MDEV processing from Λ counters. This limitation requires that all samples are accessible in order to calculate a single τ. This paper introduces a new approach to the calculation of PVAR such that a decimation rule is formulated. This decimation rule allows arbitrary samples or block of samples to be decimated, thus allowing a straight-forward block processing in a counter, and in turn enabling the counter to process at high speed many samples. The algorithm keeps the rejection of white phase noise while producing output that can be further processed to arbitrary multiples of these blocks. The multiple tau PDEV plot can now be achieved with common block processing from the hardware while significant reduction of processing power needed can be achieved. The decimation rule can be applied recursively to produce larger blocks, thus enabling this reduction of processing.

In order to utilize this technique, some guidance for counters, intermediate format and software processing is being investigated in order to illustrate to researchers and manufacturers how to best utilize this technique and facilitate accurate and correct PDEV processing in the software post-processing, thus avoiding the bias problems of Λ and Ω counters as being post-processed with incorrect decimation. The processing also produces phase and frequency estimates as to be expected from Ω counters, so this enables precision phase, frequency and PDEV processing from the same core. MDEV processing can also be achieved from the same decimation values.

References

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# Cavity-Assisted Non Destructive Detection in a Strontium Optical Lattice Clock.

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Optical lattice clocks (OLCs) recently outperformed the caesium fountains clocks providing the primary frequency standard, achieving unprecedented uncertainty, frequency stability and reproducibility, making them good candidates for more precise and stable frequency standard. Despite these improvements OLCs have not yet reached the quantum projection noise (QPN) limit and are still limited by technical noise sources.

Here we report progress on the experimental implementation and theoretical evaluation of a cavity-assisted non destructive detection on one of our strontium clock. This detection will help taking the clock towards, and eventually beyond, the QPN limit. Such a scheme permits to recycle the atoms from an interrogation to another, reducing the duty cycle of the clock. Moreover beating the QPN means entering the quantum realm, enabling quantum weak measurement and cavity spin squeezing via Quantum Non Demolition measurements (QND).

This cavity-assisted detection is expected to overcome the signal-to-noise ratio previously reported in a Mach-Zehnder based non-destructive detection [1], and thus overcoming the QPN limit for $10^4$ atoms.

Figure 1 shows the experimental setup. We measured a cavity finesse of 20000 at 461 nm and a coupling larger than 80%. We developed an heterodyne demodulation system to keep the probing laser on the cavity resonance .

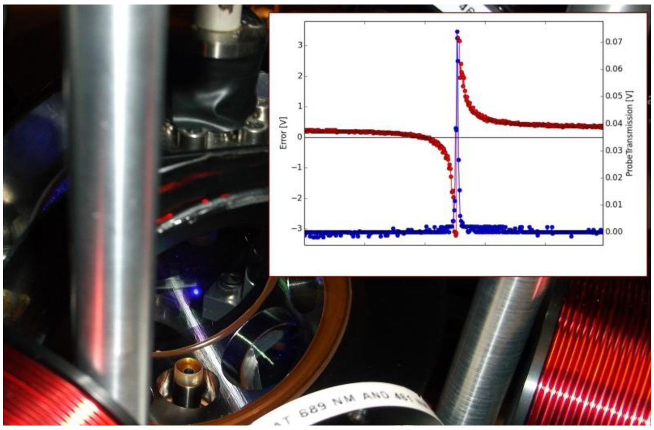


*Illustration 1: Vacuum chamber for the Sr Clock. At the center, the magneto-optical trap, surrounded by the cavity-based detection system. Inlet: resonance of the cavity.*

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# Avoiding Aliasing in Fiber Link Data Analysis

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In recent years, coherent optical fiber links have become a well established tool for frequency dissemination and a growing number of fiber-based atomic clock comparisons are going to be performed in next years. The several experimental realizations so far implemented all have some common features in the residual phase noise of the delivered signal (Fig. 1), in particular, a strong bump between 10 Hz and 30 Hz. Of course, one is interested in rejecting such high-frequency noise, since, in general, it does not contain useful information. Although these noise components can be effectively discriminated in a frequency-domain measurement, it is not straightforward to identify and reject them in a time-domain measurement. The resulting effect is well known, for instance, when evaluating the performance of optical links with the traditional estimator at full-bandwidth: if a proper procedure is not adopted, the Allan variance (AVAR), is dominated by the link high-frequency noise.

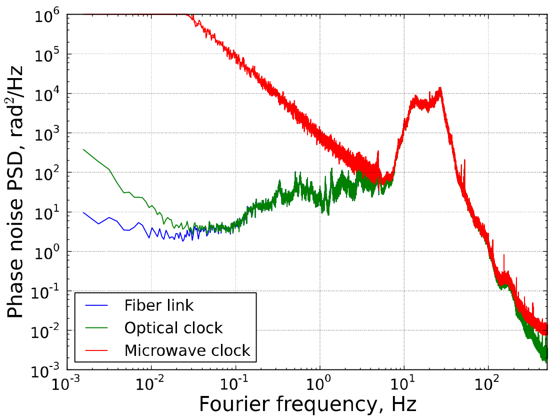


Fig. 1: the phase noise PSD of the bare link (blue) and of a link that disseminates simulated microwave and optical clocks (red and green respectively).

At the conference, we will show that this problem can be stated in terms of aliasing and that it can be avoided if sampling time $\tau_0$ and measurement bandwidth $f_h$ are chosen according to the Nyquist theorem. We recall that the AVAR is already expressed as a function of $f_h$. However, this degree of freedom is not commonly exploited as a means to reject high frequency noise or aliasing; on the contrary, it has become a common practice to use the Modified Allan Variance (MVAR). The MVAR has the advantage of mitigating the effect of the link high-frequency noise already at short averaging times, but, as a drawback, the estimation of the long-term instability is affected as well. In the case of white frequency noise (WFN), which is the typical case when atomic clocks are compared, the MVAR no longer corresponds to the classical variance (Fig. 2). At the conference, we will describe our approach [1] from a theoretical and experimental point of view. We will show also the results we obtained on the 642-km optical link we realized in Italy.

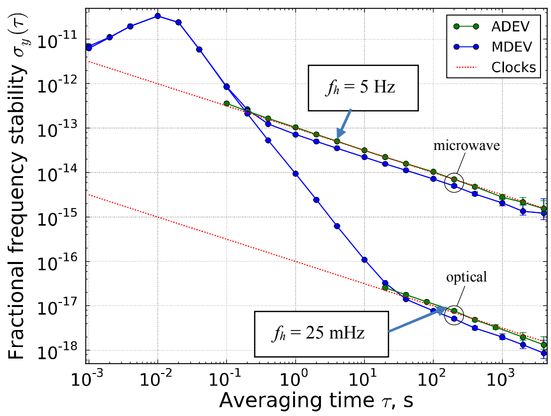


Fig. 2: the stability of the clock signals in the remote laboratory when either the full-bandwidth MDEV (in blue) or the ADEV associated with filtering (in green) are used. The dotted red lines represent the stability of the two clocks.

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# Design, modelling and characterization of a single-ion endcap trap with minimized ion-environment interaction

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A single-ion endcap trap has been designed, built and tested with the demanding needs of cutting edge optical frequency metrology in mind. Finite Element Method (FEM) modelling shows that the quadrupole potential exhibits a high efficiency of $\epsilon = 0.7$, whilst still maintaining excellent optical access. An ion-electrode separation of 0.5 mm acts to reduce the ion's anomalous heating rate, while a choice of materials with low coefficients of dielectric heating and the use of highly polished electrodes mounted on a solid copper feedthrough reduces the temperature rise at the ion.[1, 4][1]

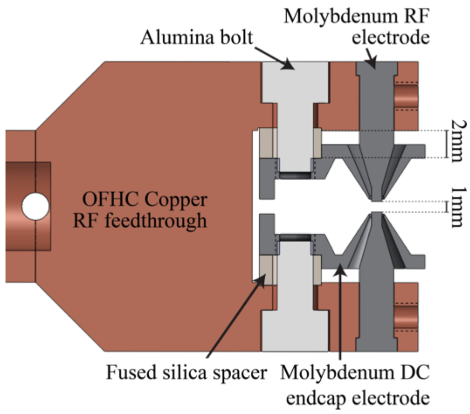


Fig. 1: Cut-away diagram of the trap

Characterisation of the trap using a single $^{171}\mathrm{Yb}^{+}$ ion allowed us to place an upper bound on the ion heating rate of $\mathrm{d}\langle n\rangle/\mathrm{d}t = 24(30)\ \mathrm{s}^{-1}$ at a secular frequency of $\omega_r/2\pi = 776$ kHz. Excess micromotion of the ion has been eliminated to the limit of the resolution of the RF photon correlation method used to detect it.

The trap's thermal properties have also been extensively modelled and measured, showing a rise in the ion's BBR environment of $\Delta T_{\mathrm{ion}} = 0.14(14)$ K [2]. Using an imaging setup with a numerical aperture of 0.4 and a photomultiplier tube with a quantum efficiency of 27%, a signal of $20000\ \mathrm{s}^{-1}$ over $50\ \mathrm{s}^{-1}$ background counts on the $^2S_{1/2} \rightarrow {}^2P_{1/2}$ fluorescence transition in $^{171}\mathrm{Yb}^{+}$ is observed.

Due to the trap's strong environmental isolation and low perturbations, the ion's environment closely approximates an ideal, isolated quantum system. When interrogating a trapped $\mathrm{Yb}^{+}$ ion on its forbidden electric octupole transition for use as a frequency standard, the trap-based contributions to the transition's fractional frequency uncertainty total $3.5\mathrm{x}10^{-19}$ for typical operating conditions [3].

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# Development and spectral characterisation of ridge DFB laser diodes for Cs optical pumping at 894 nm

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A number of research fields and applications like spectroscopy, atom interferometry, laser cooling of atoms, magnetometers, atomic clocks and frequency standards make use of lasers to prepare, manipulate, pump or interrogate caesium atoms. Distributed-feedback (DFB) lasers have proved to be convenient single-mode laser sources owing to their simplicity of use and control, frequency agility, reliability, low power consumption and compactness. Due to the simpler hyperfine structure of the caesium excited state $6P_{1/2}$, four optical transitions from the ground state $6S_{1/2}$ exist for the D1 resonance line at 894 nm, while six are present for the excited state $6P_{3/2}$ at 852 nm (D2 line). No cyclic transitions occur at 894 nm. The hyperfine level separations are also larger for $6P_{1/2}$ than for $6P_{3/2}$. Consequently, the D1 transition shows a simpler spectrum and may offer advantages for some applications with respect to the D2 line, in particular for caesium vapour cell or thermal beam atomic clocks.

DFB lasers demonstrating sub-MHz linewidth, high intrinsic wavelength and optical power stabilities and low sensibility to optical feedback can presently hardly be found at 894 nm. We report here on the characterisation results obtained from DFB laser devices designed and manufactured to meet these goals. Their architecture is based on a previous development by III-V Lab at 852 nm [1]. To strengthen chip reliability against optically-induced degradation mechanisms and for robustness of the fabrication process, the active region (optical cavity and quantum well) is Al-free. The structure is realised in a two-step epitaxial growth process to bury the Bragg grating, which enables single longitudinal mode behaviour. On the other hand, a few microns wide ridge is etched in the laser layers for lateral confinement in order to obtain transverse single mode emission.

A dedicated characterisation laser bench was assembled at LTF. Depending on the samples, the fabricated DFB lasers reach the Cs D1 wavelength at a temperature between 67 and 70°C for an injection current of 160-180 mA settled to deliver 40 mW of optical power. Under these conditions, side-mode suppression ratios larger than 45 dB are observed. Also, the linewidth at 4-ms equivalent observation time is between 640 kHz and 1.0 MHz, as retrieved from frequency noise spectral densities, whose flicker noise mostly fits the function (in $Hz^2/Hz$) $2\cdot10^{10}/f^{\,1.08}$, $f$ being the Fourier frequency. The relative intensity noise is less than $10^{-12}$ $Hz^{-1}$ at $f$ >10 Hz and less than $10^{-14}$ $Hz^{-1}$ above 1 kHz. The frequency tuning coefficients equal -1.2 GHz/mA and –20.5 GHz/K for current and temperature, respectively. These results are in line with the development objectives. A second run of fabrication is on-going where the parameters are adapted for the DFB lasers to reach the Cs D1 line at ambient temperature.

This work is supported by a European Euripides project, the French DGE and the Swiss CTI agencies.

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# High coupling phononic SH-SAW resonators for in-liquid operation

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In this communication we present integrated IDT-phononic resonators built on Y-cut $LiNbO_3$ substrate and operating on X-propagating SH-SAW with very high $K_{eff}^2$. A similar structure has been previously presented elsewhere [1] but employing RSAW on 128 $LiNbO_3$. The phononic grating is based on heavy W masses integrated with Al IDT. Within this configuration, velocity of the wave is slower than the bulk modes and the RSAW in the structure, hence being well trapped to the surface. Having a very high $K_{eff}^2$ and high dielectric permittivity the device can remain operational in relatively large dynamic ranges when loaded with liquids. In particular, this opens the possibility for non-conductive liquid measurement directly over the IDT. Measurements of conductive liquids will require isolation of the phononic IDT but still will benefit from the very high electromechanical coupling of the structure.

The described devices present two resonances, one corresponding to the mentioned SH-SAW and another corresponding to a RSAW. When contacted with water, the latter vanishes completely while the SH-SAW preserves a high performance ($K_{eff}^2$ =12% and a quality factor at antiresonance of 165) (Fig. 1 (a)). To assess the in-liquid behavior of our devices, that is their sensitivity to different densities and viscosities of the liquid media, we used different ethylene glycol-water mixtures. In Fig. 1 (b) we present the sensitivity of the antiresonant frequency to the square root of the different density viscosity products $(\rho\eta)^{1/2}$ of the mixtures. It can be observed a very high sensitivity (7200 ppm shift for 1.2 units variation of the $(\rho\eta)^{1/2}$. Additionally, frequency shifts are not linearly dependent on $(\rho\eta)^{1/2}$ as classical shear mode bulk acoustic waves, but on the product. Finally, the additional factor favouring the in liquid high performance of the SH-SAW is the very high $K_{eff}^2$ that still preserves, varying in the range of 11.7% - 13.5 % for the used mixtures.

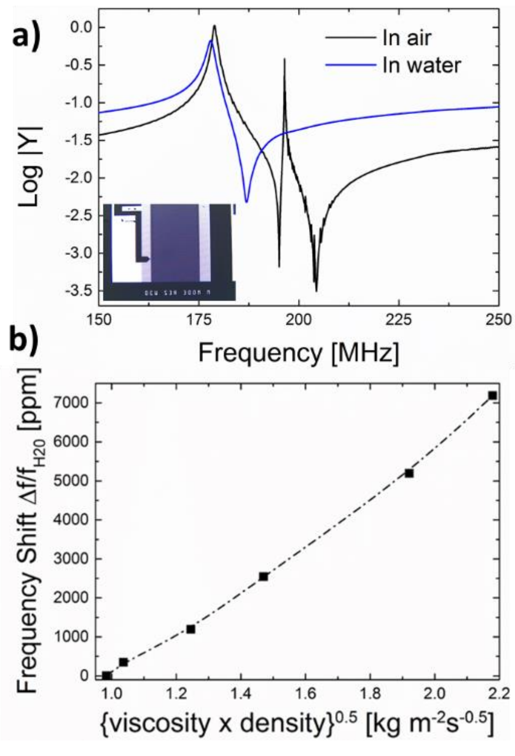


Fig. 1: In air and in water response of the device (a) and the sensitivity of the SH-SAW antiresonant frequency to the $(\rho\eta)^{1/2}$ ethylene glycol-water mixtures.

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# Optimization of Laser Radiation for CPT-based Miniature Frequency Standard

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One of the perspective pumping schemes of the miniature quantum frequency standards is coherent population trapping (CPT) scheme. It allows to avoid the use of a microwave resonator in the device, because the pumping is carried out by laser fields of optical range. The working gas of alkali atoms (Rb-87 or Cs-133) is in the cell with the buffer gas. For realization of the CPT-pumping scheme it is necessary to split the carrier laser frequency into two components (sidebands), the gap between which is equal to hyperfine splitting of the alkali atom [1].

It is clear that stability of such frequency standard is crucially depends on parameters of the pumping laser radiation such as total intensity, ratio between sideband intensities, polarization and tuning of each sideband, width of the spectrum and correlation of sidebands. In our work we investigate this dependencies theoretically and compare it with some experimental works [2].

In particular, we have developed the mathematical model which takes into account the distortion of the laser spectrum and changing of polarization inside the gas cell due to selective absorption in optically dense medium [3]. It is shown that the form and width of the laser spectrum on the input of the cell significantly affects the quality parameter of the CPT-resonance and, as a consequence, stability of the frequency standard. We analyze two types of signal detecting: the signal of forward passed radiation and the fluorescence signal. As it is shown on the Fig. 1, the contrast of forward passed radiation signal decreases with the broadening of the laser spectrum. The opposite situation takes place for the fluorescence signal.

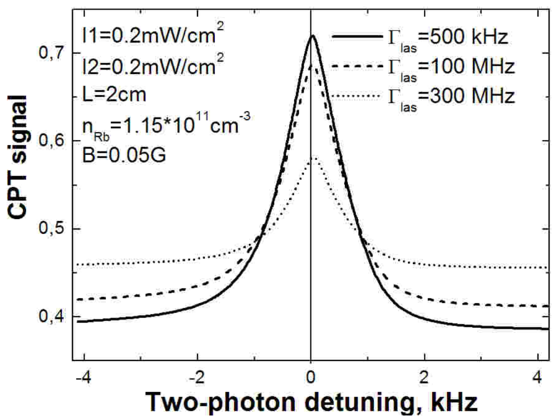


Fig. 1: Forward passed CPT-signal depending on the two-photon detuning in Rb-87 gas cell with buffer gas. Three curves correspond to different widths of the laser spectrum. Polarization of the radiation is linear (lin lin).

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# Phase locking an atom interferometer

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In atom interferometry the phase evolution of a quantum superposition state is measured with respect to a reference, *e.g.* implemented with a local oscillatory signal in the case of an atom clock and with the position of a retro-reflector for a Raman atom gravimeter. The projection of the relative phase is measured as a population unbalance on two energetic levels, so that the phase can be recovered unambiguously only over the interval $[-\pi/2; \pi/2]$. Resolving phase wrapping is a common problem for which ingenious solutions have been devised in the classical case: in distant audio recovery, for example, laser Doppler vibrometers measure the phase of a reflected beam, as well as its Doppler shift to determine the velocity of the reflecting surface [1].

In the quantum case one has to consider the effect of the measurement process on the system and specifically on its quantum coherence. Several solutions to extend the interrogation interval, hence the instrument sensitivity, have been proposed for atomic clocks [2,3] and demonstrated in atom interferometry based inertial sensing [4]; they use two or more ensembles interrogated simultaneously to monitor the relative phase evolution at different time scales to avoid phase wraps for a longer interval. We extended the unambiguous interval to probe the phase evolution of an atomic ensemble using coherence preserving measurements and phase corrections, and demonstrate the phase lock of the clock oscillator to an atomic superposition state [5]. We propose a protocol based on the phase lock to improve atomic clocks limited by local oscillator noise, which is the case of optical clocks, and foresee the application to other atomic interferometers such as inertial sensors.

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# First steps towards a Time Integrity Service for EGNSS systems, in the DEMETRA project.

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DEMETRA (DEMonstrator of EGNSS services based on Time Reference Architecture) is a research project co-funded by the European Union through the *Horizon 2020* program, aiming to develop and experiment time dissemination services based on the European GNSS. An important aspect that will be analysed in the frame of this project is the capability to deliver a time integrity service to the GNSS users, providing integrity information to improve user timing accuracy as well as positioning.

The DEMETRA Time Integrity Service is intended as a first step to test the concepts and performance of a Galileo time integrity system. Actually, the Service continuously monitors the status of Galileo satellite clocks, detecting possible anomalies and generating automatic alerts in case the satellite clock is considered unusable. The Time Integrity Service is additionally monitoring the timing parameters broadcast in the Galileo Navigation Message, such as UTC dissemination and GGTO, providing to the users a validation and performance assessment of the timing information disseminated by the Galileo System.

This experiment will show the capability to improve Galileo time and positioning services by adding a real-time Time Integrity function.

The Service will be tested for 6 months in 2016 by using Galileo public clock data which will be retrieved from the Multi GNSS Experiment of the International GNSS Service (IGS). The results of the test activities will be displayed on the DEMETRA web page, whose access will be allowed to authenticated users. Possible users of the DEMETRA Time Integrity Service are encouraged to subscribe to the Service to support the test on the time integrity concept and also to retrieve data that can be used in other activities as on board clock monitoring and performance estimation, and test on improved positioning and timing services.

*The DEMETRA project has received funding from the European GNSS Agency under the European Union's Horizon 2020 research and innovation programme under grant agreement No 640658.*

# Experimental time dissemination services based on European GNSS signals: the H2020 DEMETRA project

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On behalf of the DEMETRA consortium formed by
Aizoon, ANTARES, CNES, Deimos, Elproma, INRiM, Metec, NPL, ORB,
Politecnico of Torino, Thales Alenia Space Italy and France , UFE, Vega UK, and VTT

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In the last year an European Consortium of 15 partners from 8 different countries worked on a project, DEMETRA (DEMonstrator of EGNSS services based on Time Reference Architecture), funded by the European Union in the frame of the Horizon 2020 program, aiming to develop and experiment time dissemination services based on the European GNSS.

DEMETRA aims to be a prototype of an European time dissemination service, based on the timing signal of the European Galileo system, adding particular features like certification, calibration, or integrity, that could be of interest to some specific users like traffic control, energy distribution, finance, telecommunication, and scientific institutions. The nine services cover:

*Service 1: Digital Time broadcasting over TV/Radio links*

*Service 2: Certified Trusted Time Distribution with Audit and Verification using NTP*

*Service 3: Time/Frequency distribution over Optical Fiber*

*Service 4: Time distribution via GEO satellite*

*Service 5: User GNSS Receiver Calibration*

*Service 6: Certified GNSS Time dissemination by a Galileo disciplined oscillator*

*Service 7 : Time scale Monitoring and Steering*

*Service 8 : Time Integrity*

*Service 9: High performance network synchronization based on GNSS*

The demonstrator is currently under integration and validation in INRiM. In March the six month experimentation campaign will start in a closed loop configuration where the User Terminals are co-located with the distributed reference time to check side-by-side the capacity of distribute time to a co-located user terminal. Then, starting from June, the User Terminals will be deployed at user premises to test the services in real pilot applications.

The paper will report the development status and the first experimentation results to show potentialities and limits of the proposed time services aiming to foster the exploitation of the European GNSS time service.

*This project has received funding from the European GNSS Agency under the European Union's Horizon 2020 research and innovation programme under grant agreement No 640658.*

# Transfer of Stable Optical Frequency for Sensory Networks via 306 km Optical Fiber Link

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Optical fiber links for distribution of highly-stable optical frequencies were experimentally tested by many metrology laboratories in the past fifteen years. But recent development of new optical sensors for industrial application puts demands on a technology transfer of this high-end technology from laboratory experiments to the real industry. The remote calibration of interrogators of Fiber Bragg Grating strain sensory networks is one of important examples. We present a 306 km long optical fiber link established in the Czech Republic where a coherent transfer of stable optical frequency has been firstly demonstrated. The link between ISI CAS Brno and CESNET Prague uses an internet communication fiber where a DWDM window of 1540-1546 nm is dedicated for the coherent transfer and 1PPS signal (Fig. 1). The link is equipped with 6 bidirectional EDFA amplifiers.

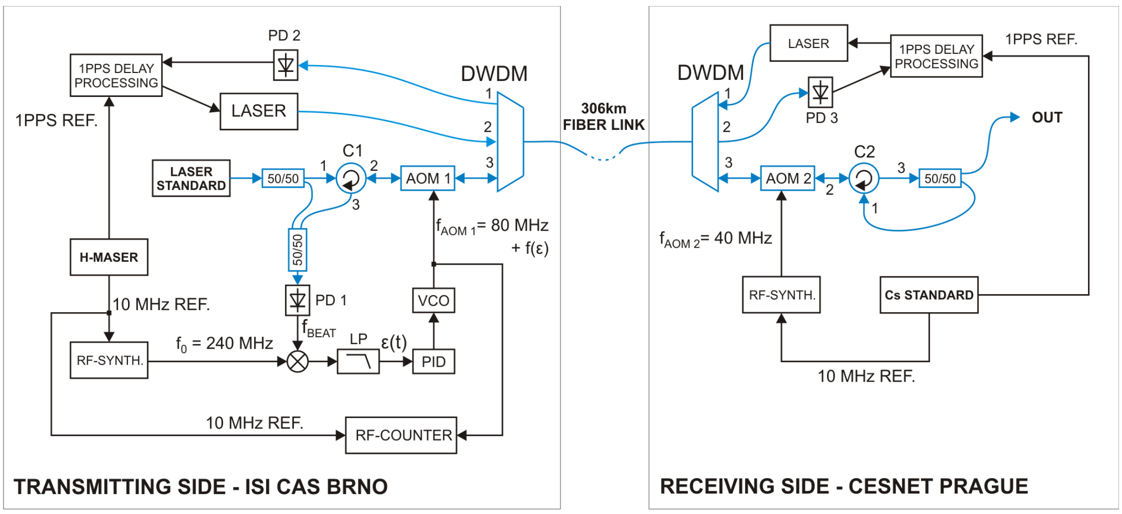


Fig. 1: The overall block diagram of the experimental optical frequency transfer setup. Legend: AOM 1, 2 – acousto-optic modulator; C 1, 2 – optical circulator; DWDM – DWDM mux/demux.; VCO – voltage-controlled oscillator; PD 1, 2, 3 – photodetector; PID – P-I-D controller.

The optical frequency standard at 1540.5 nm is used for the coherent transfer where compensation with AOM1 of the Doppler shift induced by the optical fiber is done. The servo-loop is based on a fast PID controller processing the beat-note frequency $f_{BEAT}$ which is given by the sum of AOM1 and AOM2 driving frequencies multiplied by two (each AOM is passed twice) and the actual Doppler shift. The output frequency of the VCO is continuously measured and logged by a RF counter. This enables to compute changes in the transport delay introduced by external influences on the optical line. To compare with a different measuring method a setup for analysing the transport delay of a 1 PPS signal is connected to the same DWDM mux/demux at both sides. This comparison is a subject of results of the paper.

The authors acknowledge the support from Technology Agency of CR (project TH01011254) for establishing long-haul fiber link. The issues with Doppler shift compensation have been supported by Grant Agency of CR (project GB14-36681G).

# Testing a temperature-stabilized spectroscopy chamber for an optical lattice clock suppressing the uncertainty of blackbody radiation shift

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Blackbody radiation (BBR) shift is one of major physical effects that aggregate the uncertainty of optical lattice clock (OLC). To reduce the uncertainty from BBR shift several types of OLCs have been explored by laboratories in the world by using the combination of a moving lattice and a cryogenic chamber[1], a thermo-radiometer mapping temperature distribution of surroundings[2], and a blackbody-like spectroscopy chamber with homogeneous temperature distribution[3]. In our new $^{171}$Yb OLC we will adopt the blackbody-like spectroscopy chamber near room temperature for reducing BBR shift uncertainty, however the temperature of it will be controlled actively, which have not been tried previously. The chamber was designed to have temperature sensors and a heater mounted outside of vacuum chamber like figure 1 for the convenience of calibration of RTD sensors and ultra-high vacuum operation.

The idea of temperature-stabilized spectroscopy chamber was tested preliminarily. A copper chamber shaped of a hat was machined to have 12 ports for addressing required laser beams and fluorescence detection on side of UHV. The rim of the chamber roles as a copper gasket and supporting mount of the whole body. From the air-side of the chamber 15 holes of 2 mm diameter were drilled for inserting RTD sensors, and 4 holes from UHV-side. A film heater with shape of doughnut with 100 Ohm was attached on the air-side surface to heat the chamber by using PID control feedback from a RTD sensor in the center of film heater. We measured the temperatures of every hole on the chamber during the temperature of the chamber was stabilized at slightly higher set point than the room temperature. The difference of temperatures was as small as 20 mK for the hottest and the coldest spots, which is corresponding to the BBR shift uncertainty $10^{-18}$ level, if not considered other effects.

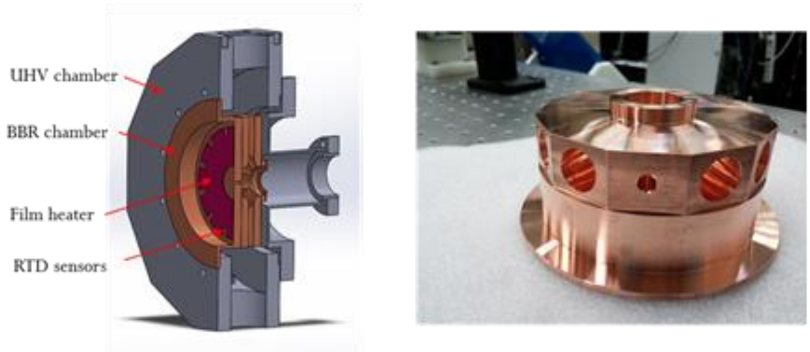


**Fig. 1:** Temperature-stabilized spectroscopy chamber and its assembly with UHV chamber.

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# Months-long evaluation of maser frequency by a lattice clock toward the steering of time scales

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An oscillation without phase jump is a prerequisite for clocks that maintain a time scale. That's why the time scales in most metrology laboratories employ hydrogen masers (HM) as source oscillators. At this point, HM have an excellent balance of the stability and reliability among other available oscillators including optical oscillators. Thus, they may continue to be the source oscillator of time scales even after the SI second is redefined by an optical transition. In this case, the benefit of using optical frequency standards instead of Cs fountains will be the capability to evaluate the HM frequency more quickly. Then, we don't need to operate optical clocks continuously. The optical clock for time keeping can be utilized for other applications from time to time.

To investigate such a possibility of intermittent operations, we demonstrated a frequency evaluation of an HM over a few months with reference to a $^{87}$Sr lattice clock. The HM is a part of the Japan Standard Time (JST) system and is linked to the International Atomic Time (TAI). Therefore, the result obtained over a few months has enabled the most accurate TAI-based absolute frequency measurement of the $^{87}$Sr clock transition [1], where the largest uncertainty was attributed to the dead time of the TAI frequency. The calibration of the TAI-TT is normally evaluated only on month basis in Circular T. To reduce this uncertainty, the TAI-TT on the specific five-day-basis of the campaign was calculated by G. Petit at BIPM Time department. Although the reduction of the signal integration from one month to five days boosts TAI-TT uncertainties, the removal of the dead time has allowed us to reach a revised absolute frequency with the total uncertainty of $10^{-16}$ level.

The frequency evaluations over a few months were also utilized for a simulation that studies the feasibility of steering a time scale by an optical clock. We assume that the HM frequency and its linear drift rate are estimated based on the evaluations performed in past 45 days. It is further assumed that this residual frequency is compensated at a micro phase stepper. Referring to the time differences of the HM from UTC(NICT) which were recorded in the JST system, it was figured out as shown in Fig. 1 that the difference between UTC and the time scale steered by an optical lattice clock would be maintained below 3 ns. We also investigated how frequently the calibration by Sr should be performed.

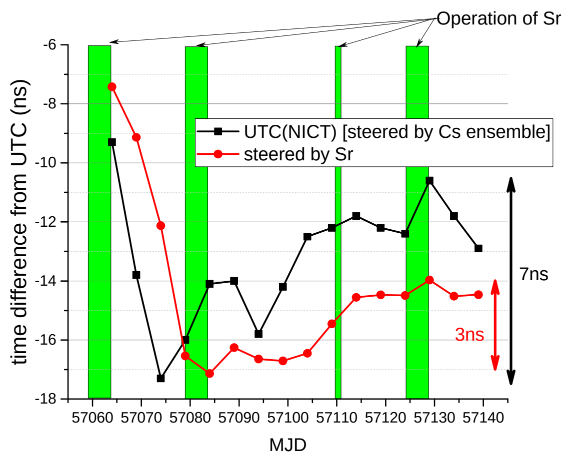


Fig.1: Simulated steering of a HM frequency with reference to a $^{87}$Sr lattice clock. Two temporarily separated measurements enable estimation of the drift rate, reducing the fluctuation later than MJD 57080.

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# Data Timing and Clock Monitoring in the Gaia astrometric mission

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Gaia is an ESA space mission launched on 19 December 2013 with the main goal to provide astrometric and spectro-photometric measurements of over one billion celestial objects. The accuracy of the astrometric parameters at the end of the mission (at least 5~years of observations) should reach the level of about 10 microarcseconds for stars of optimal brightness. This level of accuracy requires not only high-accuracy relativistic models of observations, but only a very high accuracy of all the auxiliary data entering the model. The auxiliary data include astronomical constants and parameters, the ephemeris information of both Gaia spacecraft and the whole solar system as well as the timing information of the observational data.

The timing requirements of Gaia are complicated and involve both the stability requirement over the periods of about 30000 seconds and the requirements of the absolute accuracy of the onboard time of about 1 microsecond. To meet these requirements the spacecraft has a high-accuracy Rubidium clock on board which directly meets the stability requirements.

In order to meet the accuracy requirements a special one-way time synchronization process is organized. This process coupled with the high-accuracy Gaia orbit and careful relativistic modeling [1] allows reach the accuracy of time transfer of 1 microsecond at any moment of time as well as to monitor the onboard clock frequency with an accuracy of about $10^{-12}$.

The presentation will review all ingredients of the data timing and clock monitoring processes used in Gaia.

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# Towards self spin-squeezing in a BEC atomic clock

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State-of-the-art microwave-frequency standards have reached the quantum projection noise limit [1], and using spin-squeezing is an appealing approach to overcome this fundamental boundary. Spin-squeezed states, a particular kind of entangled states, can be generated in spin ½ systems through a non-linear interaction known as one-axis-twisting Hamiltonian [2]. Recently much effort has been devoted to generating such states through state-dependent microwave potentials [3], or Feshbach resonances [4]. Both methods artificially reduce the interstate atomic interaction $g_{\uparrow\downarrow}$. We present a new method, where the system reduces $g_{\uparrow\downarrow}$ by itself without user intervention.

In [5] the two states of a $^{87}$Rb hyperfine spinor condensate exhibit large spatial separation and recombination due to the different s-wave scattering lengths $a_{\downarrow\downarrow}$ and $a_{\uparrow\uparrow}$. We show that when the two components spatially separate, the twisting interaction strongly increases and shears the spin noise distribution. Its small axis can end-up below quantum projection noise.

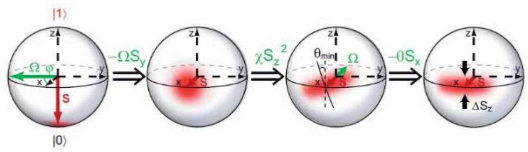

Fig. 1: Experimental sequence represented on the Bloch sphere. After an initial π/2 pulse, atomic interactions shear the spin noise distribution into a squeezed state. Adapted from [3].

In our atom-chip-generated cigar-shaped magnetic trap, we observe state separation and recombination of our $^{87}$Rb spinor condensate as well as contrast oscillations in Ramsey spectroscopy. We also demonstrate an elliptic spin noise distribution probed at the first recombination time (1.2 s). Its small axis is reduced compared to the initial atomic noise probed directly after the first π/2 pulse. We are currently investing if the reduced noise is of metrological gain which would be the first demonstration of spontaneously generated spin squeezing.

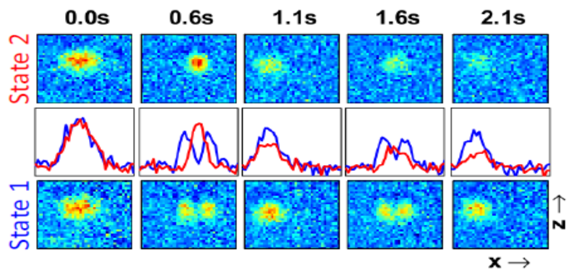


Fig. 2: State sensitive absorption images of our $^{87}$Rb spinor BEC. The trap holding time after the first π/2 pulse is indicated. Demixing and remixing is observed.

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# Hofstadter optical lattice for ultracold Ytterbium atoms

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This talk will describe new experiments probing and manipulating many-body properties of ultracold quantum gases using ultra-narrow "clock" transitions. I will focus on our experimental project, which aims at engineering a special kind of optical lattice realizing an effective magnetic field coupling to the atomic motion - *the Hofstadter optical lattice.* I will describe how such a lattice can be realized using geometric phases resulting from coherent atom-laser interactions, which mimick the Aharonov-Bohm phases experienced by charged particles moving in a magnetic field. Our specific experimental scheme uses an ultra-narrow optical transition linking the ground state to a metastable excited state in bosonic Ytterbium. (also used as ``clock" transition in Yb-based optical atomic clocks).

I will present the current status of the experiment, including spectroscopy of Bose-Einstein condensates (BEC) on the clock transition, and the observation of coherent Rabi oscillations between a BEC in the ground state and in the excited state. Optical excitation in the quantum degenerate regime is strongly affected by interatomic interactions, and spectroscopy on the clock transition probes the collective behavior of the gas, rather than the properties of invididual atoms. This can be used in particular to quantify scattering parameters for collisions between ground and metastable atoms.

# Atomic Quadrupole Moment Measurement Using Dynamic Decoupling

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We present a method that uses dynamic decoupling of a multi-level quantum probe – a single $^{88}Sr^{+}$ ion – in order to measure electric quadrupole energy shift in the $D_{\frac{5}{2}}$ level [1]. Our method allows us to distinguish this small frequency shift that depends on $m_j^2$, where $m_j^2$ is the angular momentum of level $|j\rangle$ along the quantization axis, from large noisy shifts that are linear in $m_j$, such as those due to magnetic field noise. In contrast with typical two-level dynamic decoupling schemes, here we take advantage of the six-fold $D_{\frac{5}{2}}$ Zeeman manifold of equidistant levels.

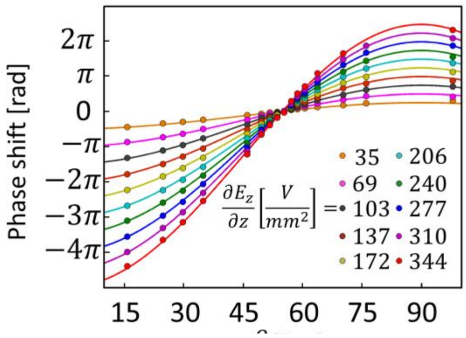


**Figure 1: Quadrupole phase shift for different electric field gradient as a function of the angle between the magnetic field and the ion's quadrupole axis. The solid lines are a fit to the entire set of data marked in filled circles, with three fit parameters.**

The electric quadrupole shift is an important systematic shift in ion-trap optical atomic clocks. In these clocks, electric field gradients are inherent to the trap and induce typical fractional shifts on the order of $10^{-13}$. Evaluating the above shift requires a reliable knowledge of the quadrupole moment of the levels involved. By using our measurement scheme, we were able to measure the quadrupole moment of the $D_{\frac{5}{2}}$ level in $^{88}Sr^{+}$ to be $\Theta\left(D,\frac{5}{2}\right) = 2.973^{+0.026}_{-0.033}ea_0$, where $e$ is the electron charge and $a_0$ is the Bohr radius. The precision of this value is an order of magnitude better than the previous measurement [3].

The prime advantages of the technique purposed here is that it requires a single trapped ion and that the dynamic decoupling sequence is performed entirely in the ion's $D_{\frac{5}{2}}$ level using radio frequency (RF) magnetic field. The latter is advantageous for several reasons. First, in contrast to measurement on an optical transition, laser phase noise does not play a role. Second, when using an RF source as the local oscillator, the measurement is not susceptible to many systematic effects, such as AC Stark shifts and Doppler shifts.

Previous methods for measuring the quadrupole shift required two entangled ions [3], or suffered from optical transition related noises [2,4]. Our method can easily be implemented in an ion trap based clock, and can assist in estimating the systematic shift of that clock resulting from the electric quadrupole coupling of the ion to the electric potential.

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# Incorporating Optical Clocks into UTC(*k*) Time-Scales

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In recent years a number of National Measurement Institutes (NMIs) have developed procedures for steering their UTC(*k*) time-scales using regular measurements of the frequency difference between the reference hydrogen maser and the local caesium fountain primary frequency standard. Integration times of at least several hours are needed due to the short-term instability of the fountain and typically only one steering correction is applied each day, but this is sufficient to limit the time offset of the UTC(*k*) time-scale from UTC to within a few ns. The stabilities and estimated systematic uncertainties of more advanced types of optical clock now greatly exceed those of the leading caesium fountains, generating interest in their use in time-scale generation [1, 2].

During a campaign of European optical clock comparisons in June 2015, carried out as part of the "International Timescales with Optical Clocks" (ITOC) project [3], the NPL $^{87}Sr$ and $^{171}Yb^{+}$ optical clocks were operated over a 26-day period. The clocks were compared with the hydrogen maser that provides the reference for UTC(NPL) using femtosecond optical frequency combs, producing frequency ratio measurements between each clock and the maser at 1-second intervals with availabilities in excess of 70%.

Using these data sets, simulations have been carried out to investigate the effectiveness of steering the UTC(NPL) time-scale to measurements from one or both of the optical clocks. Strategies for dealing with the dead times have been investigated, including the combination of measurements from both clocks, with the aim of producing a simple and robust algorithm that can be readily implemented with minimal changes to existing systems and procedures. The results of the simulations have been compared with the UTC-UTC(NPL) values published in the BIPM Circular T.

This work was performed within the ITOC project as part of the European Metrology Research Programme (EMRP). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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# Impact of turbulence on high precision ground-satellite frequency transfer with two-way coherent optical links

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Bidirectional ground-satellite laser links suffer from turbulence-induced scintillation and phase distortion. Driven by frequency transfer applications, we study how turbulence impacts on coherent detection capacity and on the associated phase noise that limits clock transfer precision. We thus evaluate not only the statistical properties of turbulence effects, but also their temporal evolution. We show an efficient two-way compensation of phase noise that is very promising for time/frequency transfer, and not yet evaluated in the literature to our knowledge. An efficient two-way cancellation of atmospheric effects in such time/frequency links requires reciprocity between up and downlink. This has been studied recently [1-4] on horizontal propagation paths and under conditions of perfect overlap between the two channels. To account for realistic turbulence and wind conditions, the asymmetry of the ground-satellite links, the point-ahead angle and the satellite cinematic, we use wave-optics propagation through turbulence for refined end-to-end simulations with the exact beam geometry. Monte-Carlo simulations allow characterizing the coherent detection in terms of heterodyne efficiency: mean value and statistical distribution. Temporal simulations provide time series and spectral density of the heterodyne efficiency and phase or frequency noises, thanks to translating phase screens following wind profiles and satellite cinematic. The presentation is twofold: first, we provide statistics on heterodyne efficiency for different turbulence strengths and system parameters. We show that to avoid large fluctuations in signal to noise ratio with frequent extinctions we need to correct at least for tip-tilt. Second, we present examples of temporal phase noise evolution for both up and downlink, like in Fig. 1. Finally, we quantify the two-way partial compensation of the phase noise and its impact on the frequency stability of space to ground clock comparisons in terms of Allan variance.

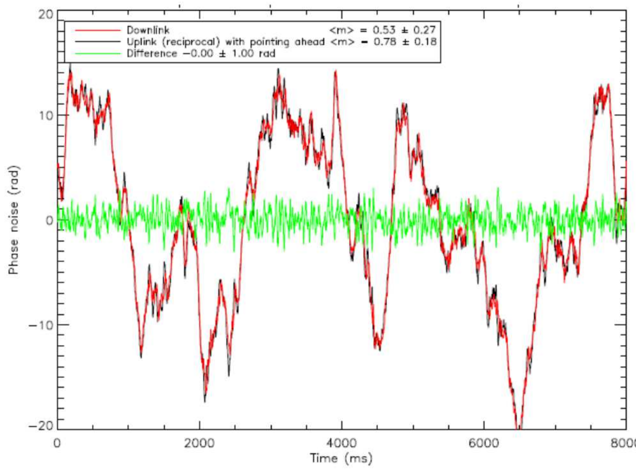


**Figure 1**: Phase noise evolution for uplink and downlink and their difference.

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# Precise frequency comparison of clocks considering the dead time uncertainty of frequency link

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In order to determine the absolute frequencies of the optical transitions, we need to measure them comparing with the caesium microwave primary standards used to realise the SI unit of time. As the frequency stability of microwave clocks at short averaging time would be inferior to that of optical clocks, the long term operation should be required to reach good stabilities and small uncertainties and it would be possible to operate them continuously for several months. On the other hand, although optical clocks have excellent short-term frequency stabilities, operating them continuously for five days would be difficult. Therefore, we need to consider the effect of the distributed dead-time and optimise measurement campaign periods to archive a precise frequency comparison between microwave and optical clocks [1, 2].

The optical frequency comb should be referenced to a frequency standard that can be linked to SI second. At the National Metrology Institute of Japan (NMIJ), frequencies of the $^1S_0$ -$^3P_0$ clock transitions in $^{171}$Yb and $^{87}$Sr are measured by using a fibre based optical frequency comb referenced to NMIJ coordinated universal time (UTC(NMIJ))[3-5]. So far the uncertainty of a comparison with UTC(NMIJ) becomes dominant part of the uncertainty of the absolute frequency measurement. To resolve this issue, we used a caesium fountain atomic clock located at NMIJ (NMIJ-F2) as a transfer oscillator [6], so that the time development of UTC(NMIJ) was consistently monitored, and we could compensate for the drift of the reference for the comb. When comparing the optical clock transition frequency with that of NMIJ-F2, we need to think about the dead-time uncertainty, because the optical lattice clock is operated for only several hours a day. Furthermore, there is a need to estimate the dead-time uncertainty for TAI and SI comparison, because the correction value and the uncertainty shown in Circular T are calculated based on data for 30 days. In other words, to reduce the uncertainty of the link between an optical lattice clock and the SI second, it is important to optimise the measurement campaign periods of the optical lattice clock and NMIJ-F2 employed as the transfer oscillator. Using this approach, the total uncertainty in the frequency measurement of the Sr clock transition could be reduced to less than one third that of our previous measurement [7].

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# Comparison of a mercury optical lattice clock with primary and secondary frequency standards

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Among the several atomic species routinely used in optical lattice clocks, mercury is a promising choice thanks to a number of favorable atomic properties. Firstly, the $^1S_0$-$^3P_0$ ultra-narrow transition used as the frequency discriminator in optical clocks is in the case of mercury very weakly coupled (respectively 15 and 30 times less than Yb and Sr) to the thermal radiation field. Moreover $^{199}$Hg has a simple structure with spin ½ allowing for a cancellation of lattice vector and tensor light shifts when alternatively interrogating the two spin states. The $^3P_1$ state has a 1.3 MHz linewidth, yielding single stage MOT cooling to temperatures as low as 40µK and straightforward loading in the magic-wavelength optical lattice. Finally, the high vapor pressure of mercury suppresses the need for an oven and thus reduces temperature gradients on the experimental setup.

However, a big challenge lies in the need for reliable cw laser sources in the UV region of the spectrum at 254, 362 and 266 nm respectively for cooling, trapping and probing the mercury atoms. Recently, several major improvements in the experimental setup yield significant improvement in the lattice trap depth, in atoms number (by a factor 10), in short term stability (by a factor 5), and, last but not least, in reliability and operability.

In this talk, we will present a new evaluation of the systematics of the mercury optical lattice clock, and the accompanying accuracy budget down to a $1.6\text{x}10^{-16}$ fractional uncertainty, almost a factor 50 improvement over our previous result [1].

We will also present an absolute frequency measurement of the mercury clock transition, obtained by comparing the Hg optical lattice clock with the atomic fountain FO2-Cs at SYRTE. This measurement has an uncertainty of $4.3\text{x}10^{-16}$, close to the limit imposed by atomic fountains and, to our knowledge, the best uncertainty to date for the direct measurement of Hg vs Cs. Furthermore, we will report on the first direct determination of the frequency ratio between neutral mercury and Rb obtained through comparison with the atomic fountain FO2-Rb, as well as a direct optical to optical comparison of the mercury and strontium optical lattice clocks at SYRTE. The value of the Hg/Sr frequency ratio that we obtain as an uncertainty of $1.8\text{x}10^{-16}$ limited by Hg and is in good agreement with the value reported in [2]. This is to our knowledge the only frequency ratio that was measured by two independent groups with an uncertainty beyond that of the SI second. These kinds of comparisons are relevant for tests of the variation of fundamental constants, as well as for assessing the reliability of optical frequency standards in view of a redefinition of the SI second.

This work is funded by EMRP/JRP ITOC and by ERC AdOC.

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# $^{87}$Sr and $^{88}$Sr optical lattice clocks at NPL

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We present an evaluation of the NPL optical lattice clock based on the $^1S_0 - {}^3P_0$ clock transition in $^{87}$Sr. The linear Zeeman and vector lattice light shifts are cancelled in the standard way by averaging the frequency of hyperfine stretched states. Other shifts are evaluated using an interleaved self-comparison of the clock, or by appropriate measurement and modelling. The self-comparison averages with instability of approximately $2 \times 10^{-15}\ \tau^{-1/2}$, aided by the stability transfer of an ultra-stable laser across a fibre comb-based transfer oscillator to the 698 nm clock laser. This 'universal synthesizer' scheme helps suppress short-term cavity noise, facilitating improved Dick-limited clock instability. We ensure reliable long-term clock operation as well as low shot-to-shot atom number fluctuations (<5%) by stabilizing the intensity and frequency of all cooling and state-manipulation lasers, which are referenced through a transfer cavity to the clock laser frequency.

$^{88}$Sr presents several advantages compared to $^{87}$Sr, e.g. there are no vector or tensor lattice Stark shifts, no first-order Zeeman shift, ten times higher natural abundance, and a simpler cooling sequence. However, these advantages come at a cost: The ultra-forbidden clock transition in bosons is not easily accessible, and s-wave atomic interactions cause large collisional decoherence and shifts [2]. Interactions may be suppressed in a system containing one or fewer atoms per lattice site [3], or potentially using a higher-dimensional optical lattice to spectrally resolve the collisional energy shift [4]. To address the large ac-Stark and quadratic Zeeman shifts associated with magnetically induced spectroscopy [5] we have implemented a modified-hyper-Ramsey spectroscopy scheme which eliminates the shift to all orders [5, 6].

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# Active optical standards using cold atoms: lasing regimes and instabilities

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The bad cavity regime of laser operation is characterized by the gain profile being narrower than the linewidth of the cavity mode. The frequency of the emitted radiation of such lasers is robust with respect to fluctuations of the cavity length, which opens the possibility to create a highly stable active optical frequency reference on the basis of such a bad cavity laser [1-3]. Such a laser may have mHz linewidth and short-term frequency stability better than achievable with modern ultrastable cavity-based frequency references. Active optical frequency standards may be realized also in less precise but more simple and robust schemes [4] for transportable applications outside the laboratory-based environment.

We investigate the bad cavity laser signal for various configuration. We study how the multilevel structure of real atoms and various inhomogeneous effects influence the main properties of the bad cavity lasers, such as the cavity pulling coefficient, output power and the linewidth. We investigate also the stability domains for cw lasing for various atomic configurations in the presence of different inhomogeneous effects.

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# Stabilization of a SESAM Mode-locked Erbium Laser Frequency Comb with an Integrated Electro-optic Modulator to an Optical Reference

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Intra-cavity electro-optic modulators (EOM) show a high performance for stabilizing fiber frequency combs to a narrow linewidth laser [1]. Hereby the large bandwidth of the EOM allows a coherent phase lock with a significant reduced noise of the comb teeth, which even enables the linewidth transfer from optical standards to slave lasers [2].

Here a polarization maintaining (PM) SESAM mode-locked all in fiber Erbium laser frequency comb oscillator with an integrated waveguide EOM [3] is stabilized to a HeNe laser. Whereas the HeNe laser is used to transfer the stability of a ring laser [4] to the frequency comb or vice versa.

The carrier envelope frequency of the frequency comb is locked to a radio frequency reference by pump power modulation, while the repetition rate of the comb is locked via the EOM, by stabilizing the nearest comb tooth to the 633 nm transfer laser. An integrated phase noise of 1.18 rad (integrated from 1 Hz to 10 MHz) was measured for the optical lock while observing a coherent peak for the optical beat.

In another experiment the EOM comb oscillator was stabilized to a low noise femtosecond oscillator at 1560 nm using the balance optical cross correlator technique [5]. Hereby the timing jitter between the optical pulse trains of both femtosecond lasers was reduced below the 1 fs area (integrated from 1 Hz to 40 MHz).

These results underline that even SESAM modelocked oscillators with a moderate free running optical linewidth (FWHM = 125 kHz – 450 kHz) can achieve a good performance by using an intra cavity EOM as high speed actuator. Additional the robust all in fiber PM design of this oscillator type opens the door to “out of lab” use.

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# ``Second Order Magic'' RF Dressing for Trapped Alkali Atoms

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Using magnetically trapped ensembles of cold atoms in microwave clocks allows to enhance the interrogation time [1]. To mitigate the perturbing effects of the magnetic trap, "magic field" configurations are employed, where the involved clock transitions becomes independent of the atoms potential energy to first order. Still, higher order effects remains and contribute to dephasing.

In atomic systems where the interatomic interactions are repulsive, like in $^{87}$Rb, the trap-induced energy shift can be compensated by the collisional shift proportional to the atomic density [2]. We propose [3] to add the technique of magic radiofrequency dressing to selectively modify the potential landscape experienced by the two clock states in a static magnetic trap.

We demonstrate that weak RF dressing can be used to cancel the relative energy shift between the clock states to both, first and second order with respect to the magnitude of the DC magnetic field in the trap. We refer to this as "second-order-magic" conditions in contrast to first-order-magic conditions, attainable in static magnetic traps, where only the first derivative of the relative energy shift vanishes. We identify and characterize these conditions for $^{87}$Rb atoms trapped in a RF-dressed Ioffe-Pritchard-type trap, compare conventional DC first-order-magic Ioffe-Pritchard traps with second-order-magic traps, and characterize the robustness of this second-order-magic potential to deviations of magnitude and polarization of the involved fields. We conclude that such radio-frequency dressing can suppress field-induced dephasing by at least one order of magnitude in comparison with "first-order magic" traps without dressing.

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# A compact double-modulation coherent population trapping clock

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A high performance passive coherent population trapping (CPT) clock [1,2] can be based on constructive polarization modulation CPT [3], in which a phase modulation is applied between the two optical components of the bichromatic laser synchronously with the polarization modulation. We call it double-modulation scheme. In this scheme, the two CPT dark states produced successively by the alternating polarizations add constructively, thus the atomic population no longer leaks to the end Zeeman states but to the desired clock states. The CPT signal of clock transition is detected with high contrast and narrow linewidth [4].

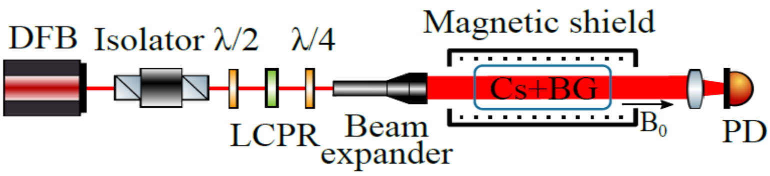


Fig. 1: Compact setup for double-modulation CPT.

Here we demonstrate a double-modulation CPT clock setup, which could be integrated into a very compact and robust setup while still maintaining its high performance. Two methods are adopted for this purpose. Firstly, we directly modulate the current of a DFB laser diode with half of Cs ground states hyperfine splitting (~4.6GHz). This method not only saves the space and laser power, but also reduces the laser intensity noise induced by a fiber EOM. Secondly, a liquid crystal polarization rotator is employed to replace an electro-optic amplitude modulator (EOAM) based polarization modulator. The polarization modulation frequency for the maximum CPT signal contrast is in the range of several kHz [4], allowing us to employ the liquid crystal based polarization switch. This low voltage driving and negligible size liquid crystal device would be an ideal choice for a compact CPT clock. The latest experimental studies will be presented at the conference.

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# First Results for the Offset Frequency Stabilization via Opto-Optical Modulation of an All-in Fiber Single Walled Carbon Nanotube Erbium Femtosecond Laser

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The stabilization of a solid state SESAM Erbium frequency comb via opto-optical modulation (OOM) of the intra-cavity SESAM was demonstrated by Hoffmann et. al. [1]. Hereby this gain modulation technique reduces the phase noise of the stabilized carrier envelope frequency compared to the standard offset frequency locking via pump power modulation significantly.

However, an OOM for a fiber based frequency comb was not demonstrated yet. A femtosecond Erbium fiber laser based on tapered fiber nanotubes (tf-CNT) is a potential candidate for opto-optical modulation, hence the transmission of the tf-CNT and so the cavities gain can directly be controlled by using the light of a single mode pump diode without the use of any optical free space parts.

In this work a soliton tf-CNT ring laser (Kphotonics LLC) pumped at 980 nm was used to investigate the OOM approach. Due to the careful ring cavity design, pump noise reduction, and the fast recovery time of CNTs a free running full width at half maximum of 60 kHz for the offset beat and 15 kHz for a comb tooth at 633 nm was measured [2]. In order to change the intra-cavity gain, light at about 1420 nm was directly fed to the tf-CNT absorber by using a wavelength division multiplexer.

To estimate the limitation of the OOM stabilization the open loop transfer function for the comb's repetition rate and offset frequency was determined for different setpoints of the OOM's pump diode. Further the characteristics of the transmission modulation of the tf-CNT absorber was studied by using cw light.

Finally the carrier envelope frequency is phase locked to a radio frequency oscillator by using whether the OOM method or the pump power modulation technique. In order to evaluate the quality of the stabilized beat phase noise measurements of the offset frequency were carried out.

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# State-of-the-art ultra-low phase noise photonic microwave generation and characterization

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Many applications such as telecommunication, radar, deep-space navigation systems and precision microwave spectroscopy are calling for ultra-stable microwave signals. Photonic generation of such signals is of particular interest because it allows transferring the unsurpassed spectral purity of ultra-stable continuous wave lasers to the microwave domain. The conversion from optical to microwave is done by synchronization of the repetition rate of a femto-second laser with an ultra-stable optical frequency reference. The microwave signal is further extracted *via* fast photo-detection of the optical pulse train. However, the photo-detection process itself introduces excess phase noise hereby limiting the stability of the optically generated microwave signal. The main limits on the purity of the microwave signal generated are the amplitude-to-phase conversion (APC) combined with intensity noise of the femto-second laser and the shot and thermal noise from the photodetector.

In order to generate state-of-the-art microwave signals we make the best of different techniques introduced recently and implement them at the highest level of performance. Firstly, we combine a very low noise optical power servo and an active stabilization of the system at the zero APC point [1,2] of a saturated fast photodetector to reject the RIN below -190dBc/Hz for frequencies above 1kHz.

Secondly, we use high-performance large bandwidth photodetector and multiply the repetition rate of our femtosecond laser to 4 GHz *via* optical interleaving of the optical pulses to redistribute the energy towards high-order harmonics of the electrical signal. This allows for increasing the photodetector saturation limit hereby minimizing the effect of the photodetection shot noise [3].

Thirdly, for ultra-precise characterization of the phase noise of the optically generated 12 GHz microwave signal, we perform a cross-correlation of the beat notes of our signal with two independent optically generated microwave references *via* a homemade FPGA-based heterodyne cross-correlator. Thus we achieve a detection noisefloor below -190 dBc/Hz for offset frequencies above 1 kHz.

Our setup currently allows exquisite absolute generation of microwave with preliminary results showing absolute phase noise below -170 dBc/Hz at 100 kHz offset frequency from a 12 GHz carrier, -165 dBc/Hz at 10 kHz and below -100 dBc/Hz at 1 Hz. These really promising figures match the best results achieved recently [4] with yet a solid margin of progression which lets us hope for unrivaled absolute microwave spectral purity in the next few weeks.

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# Investigation of high SNR Ramsey spectrum with dispersion detection in the CPT atomic clocks

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We report that the lin-par-lin Ramsey-CPT $^{87}$Rb atomic clock based on the dispersion detection technique has a promising performance. The lin-par-lin CPT configuration used in this scheme can obtain a high-contrast signal and keep the clock compact. In addition, Ramsey's separated oscillation fields technique is also applied to reduce the signal's linewidth. The dispersion detection method by orthogonal polarizers can effectively suppress background optical noise, which further improve the signal-to-noise ratio (SNR) of the Ramsey spectrum. Although the techniques involved in this clock have been reported previously [1-3], how to choose optimal working parameters has not been discussed in details to our knowledge.

In this paper, we theoretically and experimentally investigate the SNR of the Ramsey spectrum signal by varying the relative angle of the polarizer and analyzer as well as the applied static magnetic field. The theoretical calculations agree with the experimental results very well, and the optimized working parameters of the relative angle and magnetic field are obtained. According to the optimized working parameters, the short-term frequency stability of the Rb clock is estimated to be $6.6\times10^{-13}/\sqrt{\tau}$ . As we can see, This kind of atomic clock is very promising for the development of compact, high-performance vapor clock based on CPT.

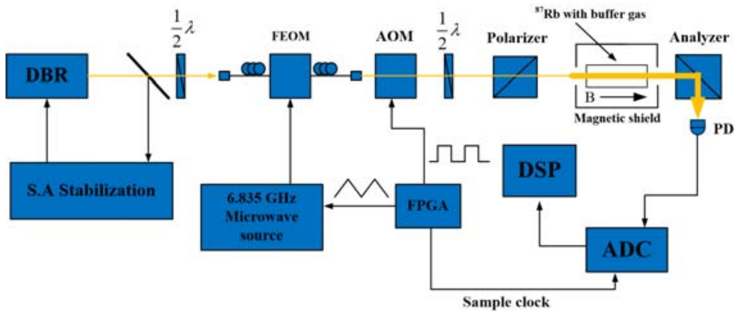


Fig. 1 Schematic diagram of experimental setup. DBR, distributed Bragg reflector laser; FEOM, fiber electro-optic modulator; AOM, acoustic-optic modulator; DSP, digital signal processor; FPGA, field-programmable gate array; ADC, analog-to-digital converter; PD, photo detector.

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# Quartz Orientations for Optimal Power Efficiency in Wireless SAW Temperature Sensors

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Sensors based on surface acoustic waves (SAW) devices demonstrate promising features for wireless applications. Besides the large sensitivity of the sensor response informative parameter to a measured physical value, the power of sensor re-radiated response is the most important factor in wireless SAW sensors. The latter factor becomes especially critical when the sensor is placed in media with high electromagnetic loss such as in living objects [1].

In temperature sensors the sensitivity is determined mainly by the temperature coefficients of frequency (TCF) or by their difference for a pair of resonators. The power efficiency requires a sufficient value of the electromechanical coupling factor ($K^2$). In fact the value of $K^2$ restricts the range of the resonator electrical coupling coefficient while the product of the latter over the quality factor Q determines the efficiency of energy re-radiation by the antenna connected to a SAW resonator. In a SAW delay line sensor arrangement, $K^2$ defines the available bandwidth of the interdigital transducer (IDT). Thus, requirements to the bandwidth enlargement directly affect the requirements to $K^2$. In every specific system the actual requirements to the $K^2$ level depend on the interrogation equipment and on the working distance.

Among available piezoelectric crystals, quartz demonstrates the largest difference in TCF achievable with different substrate orientations. A set of orientations with high TCF difference on a single substrate was suggested and tested for requirement to the $K^2$ level that was fixed at 0.03% [2]. The present work is dedicated to a detailed discussion of the relation between the required value of $K^2$ and the maximum available TCF difference on separate substrates as well as on a single substrate. Orientations with maximum difference of TCF are described for different requirements to the $K^2$ level (Fig. 1. shows the calculated achievable TCF difference for separate substrates as a function of required $K^2$). The calculation was carried out for all possible quartz substrate orientations. Selected orientations have been studied experimentally and the comparison of calculated and measured results is given.

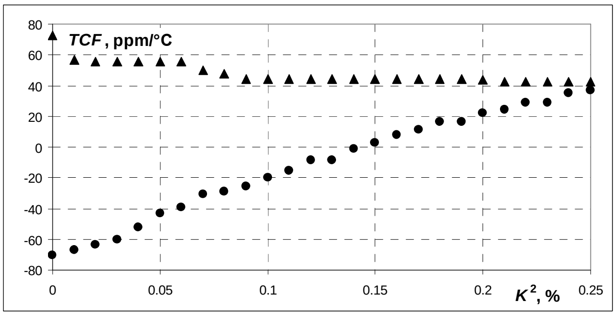


Fig. 1: Dependence of minimal (circles) and maximal (triangles) TCF on minimal required value of $K^2$ for SAW with lowest phase velocity on quartz.

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# Frequency Comparison of Two $^{40}Ca^+$ Optical Clocks with an uncertainty at the $10^{-17}$ Level

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

Based upon an over-one-month frequency comparison of two $^{40}Ca^+$ optical clocks, the frequency difference between the two clocks is measured to be $3.2 \times 10^{-17}$ with a measurement uncertainty of $5.5 \times 10^{-17}$, considering both the statistic ($1.9 \times 10^{-17}$) and the systematic ($5.1 \times 10^{-17}$) uncertainties. This is the first performance of a $^{40}Ca^+$ clock better than that of Cs fountains. A fractional stability of $7 \times 10^{-17}$ in 20 000 s of averaging time is achieved. The evaluation of the two clocks shows that the shift caused by the micromotion in one of the two clocks limits the uncertainty of the comparison. By carefully compensating the micromotion, the absolute frequency of the clock transition is measured to be 411 042 19 129 776 401.7(1.1) Hz.

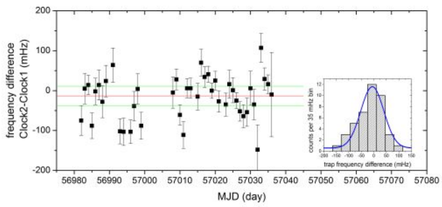


Fig. 1: Frequency comparison of the two clocks. The mean frequency is indicated by the red line and the 3σ uncertainties (σ represents the standard deviation of the mean calculated for the whole data set) by green lines. Inset: A histogram of the individual frequency measurements shown in the figure with a Gaussian fit to show the normally distributed data.

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# Compact self-referenced femtosecond Er-doped fiber laser oscillator without external power amplification

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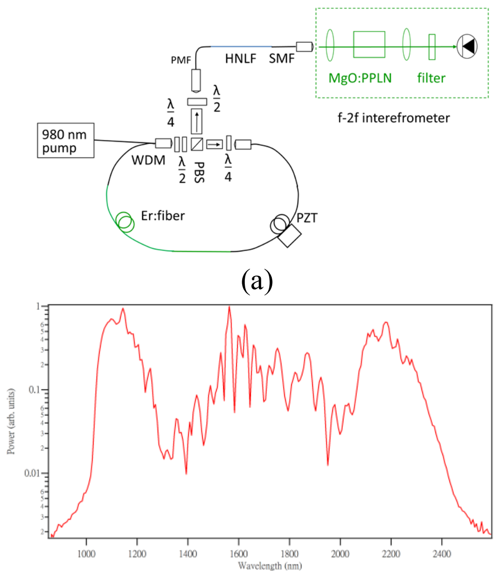
A femtosecond Er-doped fiber laser oscillator with repetition rate of 100 MHz is employed to directly drive a highly nonlinear fiber (HNLF), which generates an octave-spanning supercontinuum (SC) spectrum without using external power amplification. Compact self-referenced fiber laser comb is realized with the f-to-2f interferometer to detect the carrier-envelope-offset (CEO) frequency.

The laser oscillator is a ring cavity mode-locked with nonlinear polarization rotation similar to that published in [1] except that a micro-optics WDM is used in this experiment to couple a 980 nm pump laser into the laser cavity. A piezoelectric transducer is used to stretch the fiber for controlling the repetition rate. Figure 1(a) shows the experimental setup. By adjusting the waveplates inside the laser cavity, mode-locking can be achieved. The output from the rejection port of the laser oscillator is coupled into a polarization maintaining (PM) fiber and more than 100 mW of power is obtained from the fiber when pump power is larger than 0.7 W. By controlling the length of the single mode fiber, the laser pulses can be compressed down to 50 fs. Octave-spanning SC spectrum, which is shown in Fig. 1(b), is generated by a section of non-PM HNLF. The detection of the CEO frequency and the frequency control of the fiber laser comb are similar to that published in [2]. The stabilized repetition frequency performs a tracking instability of less than $2\times10^{-13}$@1 s. The result of controlling the CEO beat signal will be presented in the conference.




(a)

(b)

Fig. 1: Experimental setup (a) and the octave-spanning supercontinuum spectrum (b).

The f-2f interferometer used in this experiment is still made of bulk elements and the HNLF is not polarization maintaining. More compact fiber comb can be realized using the PM HNLF and in-line interferometer [3].

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# Digital Electronics Based on Red Pitaya Platform For Coherent Fiber Links

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Recent improvements and continuous research on accurate and stable frequency standards require suitable tools and techniques for frequency transfer that minimize the residual noise of the link and allow to fully exploiting these clocks in metrology applications. Several experiments performed in the last decade validated fiber links as the most performing tool for frequency transfer, reaching a statistical uncertainty the $10^{-20}$ range for thousands kilometers links [1].

The work presented here is the continuation of [2] where, the advantages of a digital implementation were demonstrated on a coherent fiber link. There, the beat note representing the length variations of the link was detected by a tracking DDS. That prototype had a contribution to the residual frequency stability of $10^{-19}$ at 1 s and had a 20-kHz tracking bandwidth, compatible with a link of 47 km. To deal with hundreds kilometers links, hundreds kilohertz tracking bandwidth is required. In this work, as an alternative, the beat note is acquired directly with a fast Analog to Digital Converter (ADC) followed by a tracking NCO (Fig. 1). This scheme minimizes the component latency and leads to a bandwidth greater than 1 MHz, compatible with thousands kilometers links. The core of this scheme is the Red Pitaya platform [3] based on the Zynq architecture, the System on Chip (SoC) of Xilinx. The platform allows remote monitoring and also implements fast Digital to Analog converters (DACs) that are used to compensate the link according to the computation done in the FPGA. This system is very compact and its flexibility allows switching easily from the classical Doppler noise cancellation scheme to the new two-way compensation scheme both in closed loop and in open loop configuration. The new electronics will be used on the Italian Link for Frequency and Time from Turin to Florence that is 642-km long. At the conference, we will present the prototype we are working on and the obtained results.

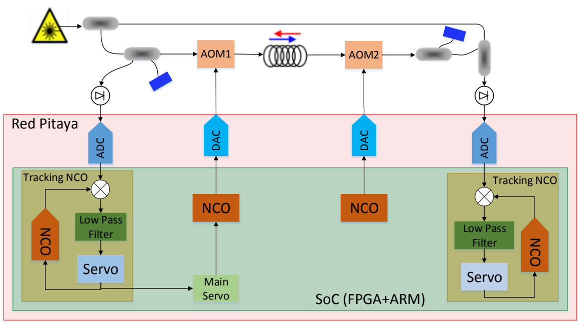


Fig.1: Proposed system for accurate clocks comparison through fiber link. The system includes detection, compensation and monitoring.

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[3] www.redpitaya.com.

# Efficient frequency tripling of a telecom laser diode

# Stabilized to iodine line at 515 nm in the $10^{-14}$ range


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Powerful and continuous wave (CW) lasers in the IR to visible range are highly attractive for various space and/or terrestrial applications including fundamental research, industrial applications, etc…. Furthermore, an efficient frequency stabilization (FS) to atomic/molecular reference is needed for a drastic reduction of frequency noise in many applications, and allows an accurate knowledge of the emitted radiation. This additional quality is fundamental in many cases such as long distance interferometry, including the gravitational wave detection (eLISA project), earth observations, inter-satellites optical communications, etc…

We have developed an original frequency tripling process based on a compact C-band telecom laser diode associated to PPLN nonlinear crystals. The optical setup is fully fibered and occupies a total volume of only 4.5 liters. It delivers up to 300 mW of green radiation (@ 3ω) with only 800 mW of fundamental power (@ω); corresponding to an optical conversion efficiency $P_{3\omega}/P_{\omega}$ ~36%. This result corresponds, to our knowledge, to the best value ever demonstrated up today for a third harmonic generation operation from infrared to visible domains in continuous wave regime (CW).

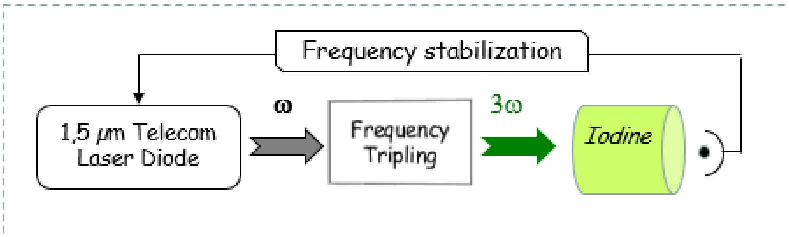


Fig. 1: Frequency stabilization scheme of the 1.5 µm laser diode

This new laser design matches well space criteria in terms of compactness, power consumption, and long term optical alignment.

To fulfill the iodine line-stabilization purpose we use the classical frequency modulation transfer technique with two counter-propagative beams in a 20 cm long iodine cell. Beams are arranged in a 6-passes configuration, in order to extend up to 1.2 m the interaction length with iodine vapor. The frequency stability evaluation is operated by comparing the frequency of our iodine stabilized telecom laser diode to an independent reference laser, stabilized to an ultrastable cavity.

A preliminary evaluation of the frequency stability reports an Allan deviation of $\sigma_y(\tau) = 6.10^{-14}\, t^{-1/2}$. The full evaluation of this original iodine stabilized 1.5 µm laser diode and its sensitivity to the major experimental parameters is under development and will be reported at the conference.

# Metrological characterization of the INRIM Yb lattice clock

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During the last few years atomic clocks based on optical transitions in ions or neutral atoms have outperformed the current time-standard, this is to say Cs-fountain-clocks, by one or more orders of magnitude in accuracy as well as in stability [1]. The CIPM recognized the narrow $^1S_0 \rightarrow {}^3P_0$ forbidden transition in neutral Ytterbium as a secondary representation of the second [3].
At INRIM, an optical lattice clock based on neutral $^{171}$Yb is now under operation and we evaluated its first metrological characterization.
The physical set-up is based on an aluminum vacuum chamber designed for wide optical access and its temperature is measured by 8 thermistors for blackbody shift evaluation. Laser radiation at 399 nm pre-slows the hot atomic beam without the implementation of a Zeeman slower. The dipole trap at the magic wavelength of 759 nm collects up to $10^4$ atoms in about 200 ms, starting from a double stage MOT at 399 nm and 556 nm. The captured atoms are then spin-polarized using the $^1S_0 \rightarrow {}^3P_1$ transition, and then the clock transition $^1S_0 \rightarrow {}^3P_0$ at 578 nm is probed by a laser stabilized to an ultra-stable cavity (Finesse F = 150.000). The cycle duration sums up to about 350 ms. The light generation at 399 nm [4], 556 nm and 578 nm [5] is based on infrared lasers and sum- or double-frequency generation in nonlinear crystals, while the lattice light is being obtained directly via a Ti:Sa laser.
At the conference, we present the first characterization of the clock, the absolute frequency measurements towards the INRIM cryogenic Cs fountain (accuracy $2\times10^{-16}$) [6]. Moreover, we describe the ongoing activities involving the Yb clock, in particular a relativistic geodesy experiment within the European project International Timescale with Optical Clocks.

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# Geodetic VLBI field-test of LIFT: a 550 km long optical fiber link for remote antenna synchronization

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Optical fiber links demonstrate unprecedented levels of accuracy in remote clocks comparisons [1] and in optical dissemination and traceability to the SI second [2]. Moreover, their use in radio astronomy has been already addressed [3], to improve the local frequency reference and time tagging of the data, as radio astronomy in general and VLBI technique in particular rely on the use of high stability reference, i.e. H masers. In Italy, we implemented a coherent optical fiber link for remote antenna synchronization between the Italian Metrological Institute (INRIM) and the Medicina radio observatory [4, 5].
In September 2015, the Medicina VLBI antenna participated to the Eur137 experiment, in tag along mode, using, as reference systems, both the local H maser and a remote H maser hosted at the INRIM labs in Turin, 550 km far from Medicina. The H Maser at INRIM is continuously measured versus a cryogenic Cs fountain [6]. The observed sources were split in two sets, each one has been observed with the associated H maser (local or remote), to compare the quality of the observations in the two set-up. The observations were correlated in Bonn and interferometry fringes have been detected with both time references along all the 24 hours of the session.

At the conference, we present the experimental set-up, the results and the analysis of the measurement campaign that provided also useful indications about the requirement of a fiber link in radio astronomy in-field operations.
We will also describe the perspectives of the experiment for future radio astronomical and geodetic campaigns.

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# SYSTEM OF FORMATION OF REFERENCE FREQUENCY FOR MODERN DATA CONVERSION

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Keywords: PLL, VCO, ADC, SoC, modern radio systems

The creation of modern radio systems with complex types of modulation, digital signal processing, etc. requires the use of high-speed analog-to-digital converters (ADCs) with high bit rate, greater signal / noise ratio, low level of distortion, etc. Most of this kind of ADC information is displayed via a parallel interface, which requires a large number of free crystal pins and complicates tracing of printed circuit boards. Using the serial interface reduces the number of pads required to interface data.

A significant problem in the organization of the serial interface in high-performance systems is the generation of a clock signal at frequencies of the order of several GHz. Often widespread production processes of integrated circuits are limited by the maximum operating frequency.

In this paper the system generate a set of reference frequencies required to clock functional blocks of data conversion investigation. The basis of the unit for generating reference frequency is phase-locked loop (PLL), which includes a voltage controlled oscillator on delay lines, phase-frequency detector, the output frequency of the VCO divider, reference divider and loop filter containing the software-configurable system leakage current compensation.

The system was implemented on the basis of a CMOS process 180 nm, and the chip area takes 0.0726 mm2 (425 × 171 micrometers microns).

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# An optical lattice clock based on $^{24}$Mg

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Optical lattice clocks are well controlled and have achieved accuracies in the low $10^{-18}$ regime and are limited by the blackbody radiation. The efforts in tackling the uncertainty of the AC Stark shift induced by the blackbody radiation in Strontium already include measuring the differential static polarizability and a shielding of the atoms against the environment.

The lattice clock at the Institute of Quantum Optics in Hannover is based on bosonic magnesium atoms. One advantage of magnesium is that shifts are well predictable. For lights elements, like Mg, atomic structure models are more accurate. Recent calculations on the BBR shift give an uncertainty of less than 1% [2]. Nevertheless, the cooling and trapping of magnesium is challenging, but we succeeded in trapping $10^3$ atoms in an optical lattice and performed a magnetically enhanced spectroscopy [2] on the strictly forbidden clock transition. We determined the magic wavelength to be 468.46(21) nm and the quadratic magnetic Zeeman shift to be -206.6(2.0) MHz/T$^2$ [3], which will be our main systematical shift. Our latest published measurements were limited by a shallow lattice resulting in a 10 kHz linewidth. We will report on the current status of the experiment with an, in terms of power, enhanced lattice and thereby reduced clock transition linewidth by at least two orders of magnitude. We also will give first estimation on the accuracy which we can achieve with our apparatus.

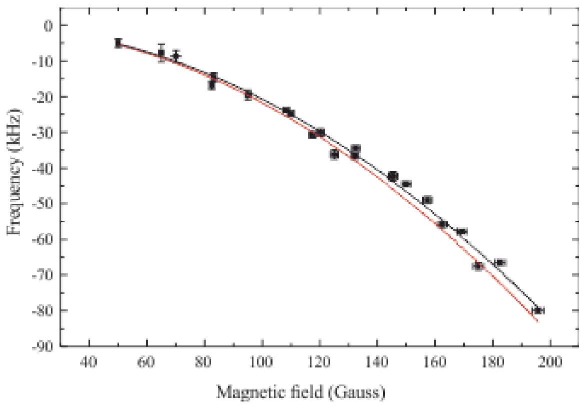


Fig. 1: Quadratic Zeeman shift of the clock transition versus magnetic field strength (black squares). The measured dependence on the magnetic field -206.6(2.0) MHz/T$^2$ agrees with the predicted dependence on the magnetic field -217(11) MHz/T$^2$ [4].

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# Sympathetic cooling $Al^+$ Ion with $Ca^+$ Ion for optical clock

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High precision atomic clocks have been not only applied to very important technological problems such as Synchronization and global navigation systems, but also to the fundament precision measurement physics .Single $Al^+$ ion become one of the most optimum selection system due to its very low blackbody radiation effect which dominates frequency shifts in other optical clock systems. Up to now ,The $Al^+$ ion still could not be laser-cooled directly because of absence the 167nm DUV laser. So Sympathetic cooling is a viable method choice to solve this problem. In this work, We use one laser cooled $Ca^+$ to sympathetic cool a $Al^+$ in linear Paul trap. In order to increase loading aluminum ion efficiency , Compare to using laser ablation atom producing ion ,we got a much lower velocity atoms sprayed from a home-made atom oven, which will make the sympathetic cooling much easier. By the method of precisely measuring the RF resonance frequency of the ion pair ,finally We proved we obtained the $Al^+$-$Ca^+$ ion pair witch will be used to QLS optical frequency standard. by sideband cooling method we succeed in cooling the Ca+ to the ground state with more than possibility 95% .The Quantum-logic-Spectroscopy experiment is in progress.

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# Recent progress in the development of a hydrogen maser in the $TE_{111}$ mode

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We present the recent progress in the development of a hydrogen maser in the $TE_{111}$ mode. Hydrogen masers use the transition at 1420.405 MHz between the two hyperfine levels $F = 0$ and $F = 1$ of the $1s_{1/2}$ ground state of the hydrogen atom [1]. Standard hydrogen masers are heavy devices which are based on the use of a $TE_{011}$ cylindrical cavity with dimensions of the order of 27 cm [1]. In contrast, the $TE_{111}$ mode is the lowest frequency mode of a cylindrical cavity in the usual regime $D/L < 0.985$ where $D$ and $L$ are the diameter and the length of the cavity, respectively [2]. In comparison with the standard masers, the $TE_{111}$ mode makes thus possible to reduce dimensions significantly to obtain resonance at 1420.405 MHz, which is very interesting for space applications and in particular in the context of the global positioning system.

The design of the upper und lower parts of the maser were studied in order to obtain a compact model. The figure 1 shows a drawing of the upper part of our hydrogen maser. The cavity is made of aluminum and is composed of two halves which clamp a thin Teflon FEP sheet (0.125 mm). This sheet is used as a septum in order to create two storage regions in the cavity. This is compulsory because the $TE_{111}$ mode exhibits two regions with opposite directions of the magnetic field. The measured frequency of the cavity at room temperature is 1420.610 MHz. Therefore in order to obtain the resonant frequency in vacuum, the working temperature of the maser should be around 40 °C. The frequency of the cavity is tuned by using a varactor diode, which allows a tuning range of 60 kHz. The loaded quality factor of the cavity with the teflon sheet is 13600. The cavity is surrounded by a thermal screen, a solenoid, three magnetic shieldings and a vacuum bell. Four ovens are used for the temperature control of the maser and a temperature stability of $10^{-4}$ K is expected.

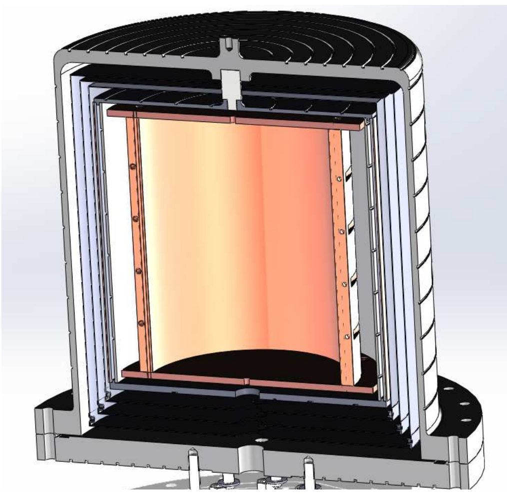

FIG. 1 – Upper part of our model of compact hydrogen maser.

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# In-situ characterization of AlN-solidly mounted resonators at high temperature

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Monitoring processes under harsh environmental conditions, particularly high temperatures (>300°C), is one of the most challenging tasks in the sensors field. Among the variety of devices that can be used for such applications, acoustic wave resonators have been widely investigated due to their low cost and good performance. One of the most explored devices is the surface acoustic wave (SAW) resonator achieved by pattering interdigital transducers (IDT) based on different Pt alloys on top of single-crystal langasite substrates. Although SAW devices have proven to fulfill high temperature requirements [1,2], they still have the drawback of using long and narrow metallic strips for the IDT, which are subjected to destructive agglomeration. As an alternative, thin film bulk acoustic wave resonators (FBAR) are promising candidates. In a previous work, [3] we showed that solidly mounted resonators (SMR) using piezoelectric AlN can stand temperatures as high as 700ºC in vacuum for more than 24 h without considerable deterioration in performance after annealing.

Here we present in-situ electrical characterization of SMR at up to 400°C in air at atmospheric pressure. The devices are composed of $SiO_2$/Mo Bragg mirrors and piezoelectric stacks of Ir/AlN/Ir. Fig. 1(a) shows the variation of the resonant frequencies with temperature, from which it can be derived that temperature coefficient of frequency is constant for the whole temperature range. In addition, experimental results show that the electromechanical coupling factor is also almost preserved, with slight improvement for the lowest temperatures. Regarding the quality factors, it keeps and almost constant value at antiresonant frequency with slight improvement at high temperature, whereas it gradually degrades at resonant frequency upon increasing the temperature, especially above 350ºC (Fig. 1(b)), due to an increase in the series resistance. We attribute this problem to the variability of the RF measurement fixtures contacts at high temperatures, which are currently being improved.

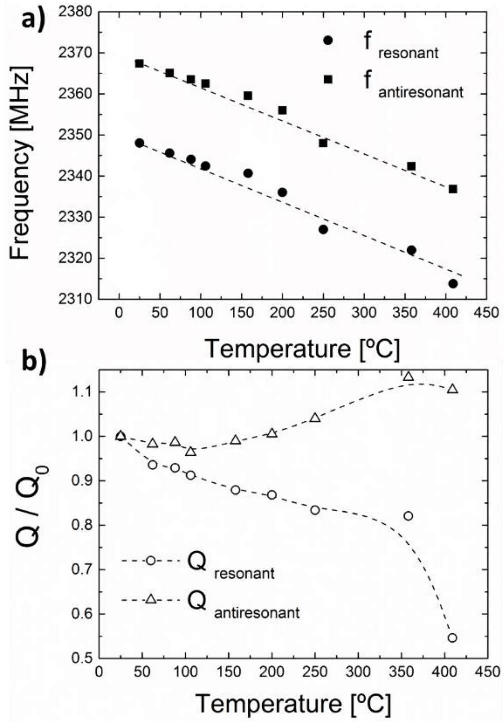


Fig. 1: In-situ resonant and antiresonant frequencies for the 25°C-400°C range (a) and the corresponding evolution of their quality factors (b).

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# Validating frequency transfer via a stabilised fibre link for optical clock comparisons

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Comparisons of remote optical clocks [1] with uncertainty $\sim 1\times10^{-18}$ require careful validation of the frequency transfer carried out via phase-stabilised fibre links connecting them. This differs from assessing the performance of a link itself: searching for fundamental limitations (systematic shifts) of a link, we minimize the statistical uncertainty by analysing long, continuous segments of data using phase-averaging [2]; the instability falls off as $\tau^{-1}$ or even $\tau^{-2}$ over some range of averaging time $\tau$. In an optical clock comparison, properties of the clocks dictate the experiment and data analysis. Interruptions in the clock availability increase the statistical uncertainty for the frequency transfer: if there are many interruptions, the instability falls off as $\tau^{-1/2}$. Campaigns may last several weeks, so external influences (weather) give different link operating conditions. However, double-link set-ups ("loops") allow us to monitor link performance and filter data, minimizing uncertainty contributions of the link to the experiment. Here, we present link data validation and data selection during a recent comparison of two Sr clocks located at SYRTE and at PTB separated by 700 km line-of-sight [1].

We focus on the validation of the German section of the fibre link from PTB to Strasbourg (Strb), which employs fibre Brillouin amplification [2] and is terminated by a repeater laser station [3] in Strasbourg. In a loop-back configuration (PTB→Strb;Strb→PTB), a beat is generated between the frequency $\nu_r$ transferred back to PTB and the frequency $\nu_s$ sent, giving the frequency transfer error $\nu_\Delta = \nu_r - \nu_s$. Under certain assumptions, this gives an estimate for the frequency transfer error in Strasbourg. For validation, the continuous stream of 1s-link-data is segmented into 1000s-intervals and the mean transferred fractional frequency offset $|y_\Delta|$ and overlapping Allan deviation (OADEV) are calculated for these intervals. For both variables, we observe distributions (Fig. 1) that allow finding meaningful link data validation criteria: each 1s data point in interval is marked valid, if both $|y_\Delta|\leq 5\times10^{-18}$ and OADEV(250s) $\leq 4\times10^{-17}$ (equivalent to approximately $5\sigma$ and $10\sigma$, respectively). The uncertainty contribution of the fibre link to the overall clock comparison is kept below $5\times10^{-18}$ already by the validation criteria themselves, and overall drops two orders of magnitude below the uncertainty of the participating clocks. The method can be readily incorporated into online monitoring and will facilitate future clock comparisons.

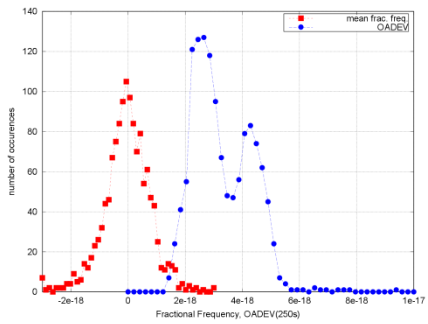


Fig. 1: Distribution of the mean transferred fractional frequency offset $y_\Delta$ and the OADEV(250s), here shown for valid 1000s-intervals of the campaign.

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# Deep Space Navigation using X-Ray Pulsar Timing with a High Performance Space Atomic Clock

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In recent years space agencies around the world have been exploring the use of X-ray pulsar timing for spacecraft navigation [1], a technique commonly referred to as 'XNAV'. Here we describe a recently completed study for ESA on the feasibility of this for deep space navigation. Simulations have been used to identify the best combination of X-ray pulsars with respect to performance considering current and future X-ray instrumentation. The potential technique would allow increased spacecraft autonomy, improved position accuracies in certain scenarios and lower mission operating costs compared to the NASA and ESA Deep Space Networks.

Potential instrumentation has been designed in the context of the Mercury Imaging X-ray Spectrometer for ESA's BepiColombo mission to Mercury and is in development. Simulations of navigation errors based on the characteristics of this show that the pulsar PSR B1937+21 has the potential to allow a positioning accuracy of order 2 km in the direction of the pulsar, for ranges up to 30 AU (the range to Neptune). This could be achieved autonomously on the spacecraft using a ~10 hour observation of the pulsar by the instrument together with a high performance atomic clock. Furthermore, observations of three or more pulsars in sequence could in principle be used to obtain a three-dimensional XNAV position solution. A good combination would be PSR B1937+21, PSR B1821-24 and PSR J0437-4715.

X-ray instrumentation suitable for use as a subsystem must be designed to use only modest spacecraft resources. Furthermore, absolute time accuracy on-board a spacecraft is one of the limiting factors for spacecraft autonomy. An on-board atomic clock with $\sim 10^{-17}$ stability over for example 10 or 20 years, such as a space optical clock, would mean that only limited contact with Earth-based systems would be needed by the spacecraft for navigation purposes during such mission lifetimes. Furthermore, such a clock could also be complementary to some advanced space experiments.

The present limiting factor in XNAV performance is often due to the pulsar astrometric positions. New developments in astronomy, such as the Square Kilometre Array (SKA), are driven by goals to detect, for example, gravitational waves using pulsars. Such research will lead to more accurate pulsar positions which in turn will enable improved XNAV performance. Considering such future possibilities, we comment on the potential benefits that an XNAV system combined with a high performance space atomic clock could offer to advanced space experiments.

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# Transparent thin film bulk acoustic wave resonators

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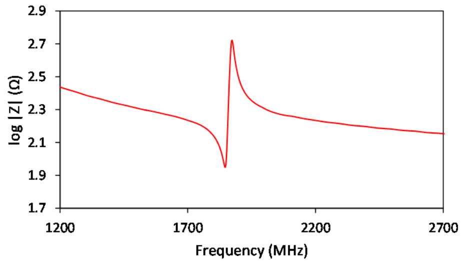
Transparent electronics have interesting applications in the field of electronic consumables. Wearable devices, intelligent windows or new concepts of smartphones and screens could certainly benefit from the integration of fully transparent devices on different substrates. Film bulk acoustic wave resonators (FBARs) have demonstrated their usefulness in different areas, from communication filters [1] to high sensitivity sensors [2]. Modifications in their fabrication process to make them fully transparent while maintaining a good performance could lead to a new generation of devices.




(a)

(b)

Fig. 1: Frequency response of the transparent resonator (a) and photograph of a sample containing a set of transparent devices placed on top of a retro-illuminated display (b).

In this work we present fully transparent FBARs with a solidly mounted resonator (SMR) structure. A 0.6 mm-thick Corning Glass® was used as substrate. The acoustic reflector was made of 7 alternated layers of $SiO_2$ and $Ta_2O_5$. A 250 nm-thick layer of sputtered Indium Tin Oxide (ITO) was used for both the top and bottom electrode. Aluminum nitride (AlN) was the chosen piezoelectric material, which also presents a high optical transmittance. To improve the response of the devices, in some samples a 100 nm-thick capping layer of room-temperature growth AlN was used to prevent the direct contact of the active layer with the ITO electrode.

The SMRs displayed a resonant frequency $f_r \approx 1840$ MHz, a quality factor Q around 100, and an electromechanical coupling coefficient $k^2$ up to 4% while keeping a good transparency when placed on a retro-illuminated display, as shown in figure 1. Even though the performance of the devices should be improved, these results are a promising first step in the integration of fully transparent BAW resonators.

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# Long-Term Frequency Stability Improvement of OCXO using CSAC

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Nowadays, the Chip scale atomic clock (CSAC) gives great potential for wide range of commercial, industrial and especially military and aerospace systems requiring superior long-term frequency stability. Compared to OCXO, the main disadvantage of the CSAC is their higher phase noise (Fig. 1). Our research is focused on digital signal processing of RF signals using the high-speed A/D, D/A converters and FPGAs. Proposed method of OCXO long-term frequency stability improvement utilizing CSAC (Symmetricom SA.45s) will be described in this paper. In this way, the superior behavior of the CSAC can be incorporated to many existing strategic RF and microwave systems as well.

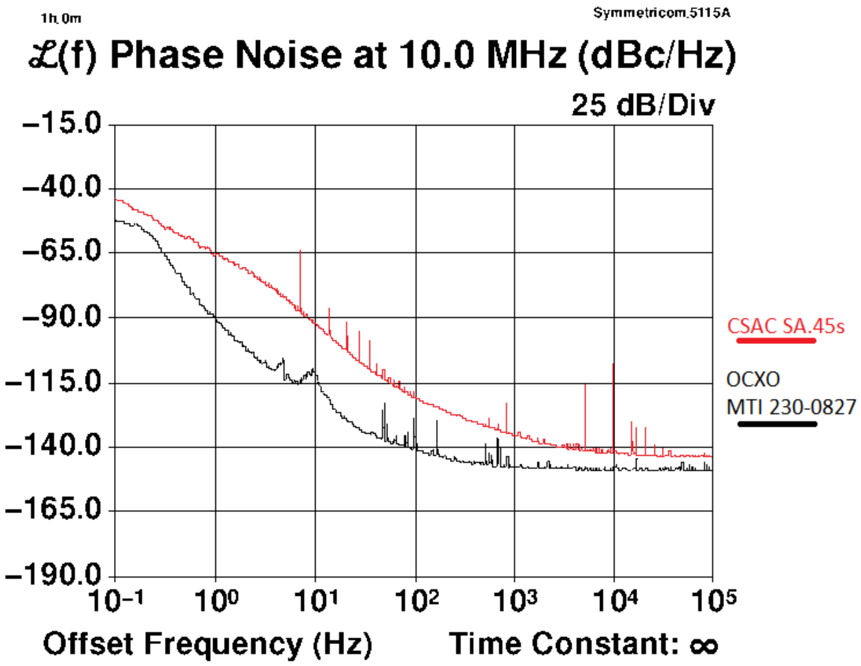


Fig. 1: Phase noise comparison of OCXO (MTI 230-0827) and CSAC (SA.45s)

# The LNE-SYRTE cold atom gravimeter

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I will introduce the absolute Cold Atom Gravimeter (CAG) which has been developed in the frame of the LNE watt balance project. This instrument has been operational since 2009, and participated successfully since then to several international comparison campaigns [1, 2]. It uses atom interferometry to perform an absolute measurement of the gravitational acceleration g, with a best sensitivity as low as 5.7 $10^{-9}$g/Hz [3], a high cycling rate of about 3 Hz and a relative accuracy of 4 parts in $10^{9}$ [2].

In my talk, I will present this gravimeter and its performances. I will also briefly present instruments based on other technologies, and in particular the superconducting relative gravimeter iGrav which has been measuring in the gravimeter laboratory since more than two years.

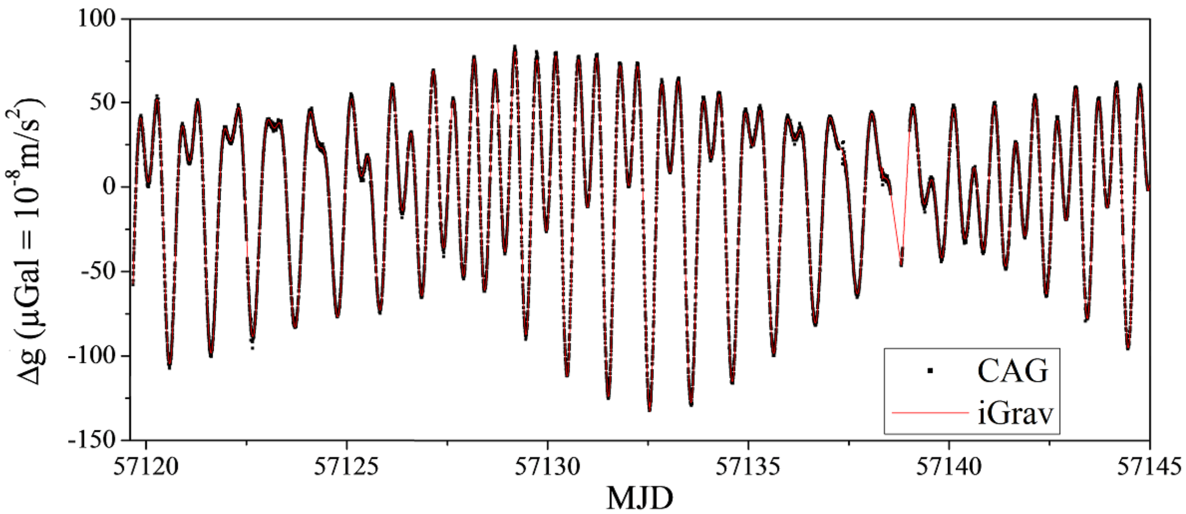


Fig. 1: Continuous gravity measurements of the Cold Atom Gravimeter and the iGrav superconducting gravimeter

The comparison between these two instruments allows on one hand for an efficient and accurate calibration of the superconducting gravimeter and on the other hand for the possibility to separate real gravity fluctuations, such as due to environmental changes, from fluctuations of the systematic effects of the instruments. I will finally discuss our efforts to improve the long term stability and accuracy of the CAG and to bring the uncertainty in the measurement of gravity acceleration at or below the $10^{-9}$g level.

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# Photonic Oscillators: Beyond the State of the Art

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Photonic oscillators are based on generation of RF (microwave/mm-wave) signals by beating equally spaced coherent harmonics of light produced by one, or multiple lasers on a fast photodiode. The frequency of the RF signal corresponds to the equally spaced interval between the harmonics, and thus it can be readily selectable. The phase noise of the RF signal corresponds to the phase noise of the optical signal that generated it.

The first instantiation of high performance photonic oscillators is the opto-electronic oscillator (OEO), where modulating a laser produces the harmonics. An opto-electronic loop provides the feedback signal to the modulator for sustained oscillation. A long length of low loss optical guide produces a long delay in the feedback loop, resulting in high spectral purity of the generated signal. A variation of this architecture (the coupled OEO, or COEO) combines an optical loop, as the source of light, with the electronic loop that typically provides filtering, gain, and phase adjustment, through the modulator This configuration has an optical output in the form of a multiple light harmonics (known as a frequency comb) and a highly spectrally pure RF output due to the role of the optical loop in generating a relatively wide optical comb.

The next generation of photonic oscillators employs a mode lock laser, the output of which can directly produce an RF signal by beating on a photodetector. To obtain a high spectral purity at the output, the laser must have low noise, a requirement that has been difficult to meet with passive mode lock lasers. The advent of femtosecond (fs) mode lock lasers has remedied this shortfall. The technique of two point locking of the frequency harmonics generated by fs lasers allows division of the phase noise of a high quality cavity stabilized external laser that locks the center frequency of the comb.

Despite their success, fs comb based photonic oscillators are not well suited for operation outside the laboratory. Optical Kerr combs generated by pumping a whispering gallery mode (WGM) in a micro-resonator with continuous wave light provide the high performance of photonic oscillators in tiny form factors, suitable for field applications. They have produced unprecedented mm-wave signals with higher spectral purity than electronic oscillators in chip scale form factors.

In this presentation a review of photonic oscillators will be followed by recent results obtained with optical combs. The latter part of the talk will be focused on the emerging capabilities based on optical WGM micro-resonator oscillators. In particular, two new approaches based on the Kerr comb in an OEO loop, and a tunable configuration spanning 10 to 100 GHz will be discussed. New advances in stabilization of the Kerr comb oscillator to atomic transitions to realize high performance miniature atomic clocks will also be presented. These new approaches produce capabilities beyond the current state of the art of photonic oscillators.

# Towards an $Yb^+$ optical clock with a BBR uncertainty below $1x10^{-18}$

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The highly forbidden electric octupole (E3) transition in $^{171}Yb^+$ is a promising candidate for a future redefinition of the second. Its long excited state lifetime (>6 years) and small systematic shifts, as well as its sensitivity to violation of Lorentz invariance [1] and changes in the fine structure constant [4], have made it an exciting system to explore as both a next-generation atomic clock and for cutting-edge tests of fundamental physics. Recent developments in ultra-stable lasers, ion traps, and hyper-Ramsey spectroscopy techniques, allow the majority of the systematic shifts to be controlled at the $10^{-18}$ level under optimum conditions [2,3]. This leaves the black body radiation (BBR) shift, caused by the interaction of thermal radiation with the ion, which is presently the dominant cause of systematic uncertainty. This is despite the absolute magnitude of the shift being relatively small, with a shift of only approximately $1\times10^{-16}$ expected at room temperature.

With careful consideration to the design of the ion trap, and by modelling or measuring the temperature of all components, it has been shown that the thermal environment experienced by the ion can be known to ±0.14 K. This reduces the systematic uncertainty associated with the determination of the temperature environment of the ambient radiation to $2\times10^{-19}$ [2]. In order to correct the transition frequency to absolute zero, it is necessary to know the differential static polarizability between the ground and excited states of the clock transition. The best published experimental value for this parameter has a 50% uncertainty – which results in a systematic uncertainty of nearly $5\times10^{-17}$. Reducing this systematic to below $1\times10^{-18}$ requires knowledge of the differential static polarizability to better than 1%.

Initial measurements of differential polarizability at 671nm have determined the so-called "magic" wavelength at which the ground and excited states are equally perturbed by the laser. Further, by probing the ion with light at near-IR and mid-IR wavelengths (~ 7 μm), we can trace out the decay of the differential polarizability curve towards the static value. The results of these measurements will be presented at the conference

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# Cold Highly Charged Ions for Highest Precision Spectroscopy

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With the ability to simultaneously control both the excitation and the motional degrees of freedom of individual quantum objects, atomic physics has reached a degree of accuracy which defies comparison in the experimental sciences. Immediate consequences have been the development of atomic and optical clocks. These are meanwhile capable of measuring subtle effects of relativity and even of setting upper limits to possible variations of fundamental constants. In principle, the binding energy of atomic electrons in their ground state is sensitive to all levels of Standard Model physics. Their wavefunction adapts to all small contributions arising from all known interactions. This universal pattern of sensitivity is expected to appear again if forces beyond the Standard Model were to exist.

In highly charged ions (HCIs), the wavefunction of the optically active electron is much reduced in size. This implies magnified sensitivity to electron-nucleus interactions and QED terms in general, and an extremely suppressed sensitivity to external field perturbations. Further, E1 forbidden optical transitions found near level crossings in HCIs are extremely sensitive to possible drifts in the fine structure constant. This favorable combination of properties has been widely recognized as a bonus for precision studies with HCIs and the development of HCI based clocks in many recent theoretical works. However, there has been a persistent experimental problem hindering improved photonic studies with HCIs. All known sources of HCIs produce them at high temperatures, typically in the MK regime. Bringing these translational temperatures down to the mK scale has been a long and elusive target of various experimental groups.

We have developed an experiment for retrapping, cooling and high-precision laser spectroscopy of HCIs. It is based on continuously laser-cooled $Be^+$ Coulomb crystals in a linear cryogenic Paul trap for stopping the motion of externally produced HCIs and sympathetically cooling them below 250 mK. This cooling induces the formation of stable mixed crystals – down to a single HCI cooled by a single co-trapped $Be^+$ ion [1]. The strongly suppressed thermal motion of the embedded HCIs offers novel possibilities for investigation of questions regarding the time variation of fundamental constants, parity non-conservation effects, and quantum electrodynamics. The current step is high-precision spectroscopy of the $^2P_{3/2}$ - $^2P_{1/2}$ M1 transition at 441 nm in cold $Ar^{13+}$ ions. Adding HCIs to the quantum toolbox is the ultimate goal within the scope of next-generation experiments, which are currently being set up. One aims at applying quantum logic schemes to HCIs and developing an HCI optical clock, the other one at direct VUV frequency comb spectroscopy of transitions in HCIs.

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# Interference detection and countermeasures in a GPS-disciplined chip-scale atomic clock

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We describe a smart clock controller (SMACC) intended to complement a commercial disciplined clock so that it becomes 'spoof proof', i.e. hardened against several classes of GPS jamming and spoofing attacks. The controller uses a multifactorial approach to evaluate the validity/integrity of received GPS signals based on a number of observables as well as clock correction modelling. In particular, multiple GNSS receivers in combination with the stability of a chip scale atomic clock (CSAC) is used to build a multi-layered situational awareness aimed to provide resilience against seamless GPS time hacking attacks[1]. Moreover, the stability of the CSAC will provide enhanced holdover operation in the case of spoofing or jamming attacks. The 'spoof proof CSAC SMACC' is built using inexpensive off-the-shelf commercial components.

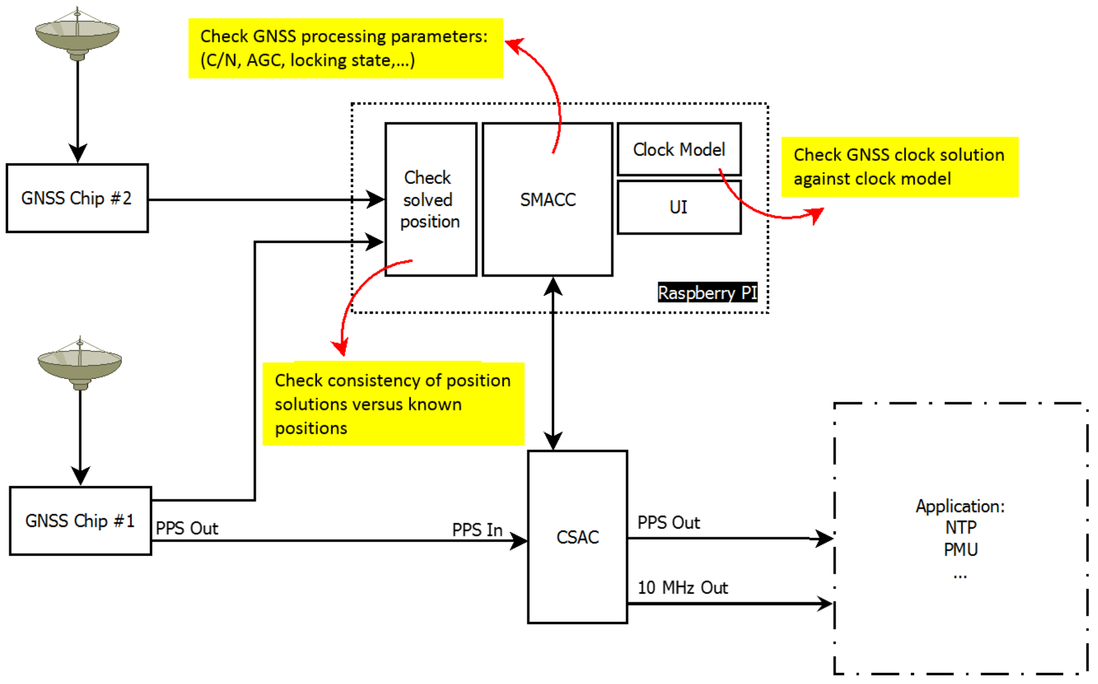


Fig. 1: Conceptual sketch of a smart clock controller aimed to harden a GPS disciplined clock against 'time hacking' in the form of GPS jamming and spoofing attacks.

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# On temporal correlations in high resolution frequency counting

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We analyse the autocorrelation of time series of gapless frequency data from different high resolution counters. We find that the high resolution ('CONT') frequency counting process of the 53230A type counter imposes long term correlations in the output data. We show how such correlations may be due to smoothing processes with long term memory. Finally, we demonstrate how alternative finite window smoothing filters may be applied to a stream of raw (i.e. not smoothed) continuous frequency data, yielding resolution enhanced frequency estimates without spurious long term correlations.

# Influence of induced stress on AlN-Solidly Mounted Resonators

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Strain sensors are widely used in many applications, from simple strain measurements to pressure or force sensors. Aluminium nitride (AlN) solidly mounted resonators (SMRs) show high stress coefficient of frequency (SCF), which can be easily used in these applications. In this communication we present the assessment of AlN-based SMRs (SCF, $k^2$ and $Q$) when the substrates are subjected to a controlled deformation. The SMRs are built on top of 525 µm-thick (100) silicon substrates cut into 6 mm-wide by 30 mm-long rectangular strips. The devices consist of Mo/AlN/Mo piezoelectric capacitors lying on top of a five-layer acoustic reflector that alternates $SiO_2$ and Mo low and high acoustic impedance films. All the films are grown by the sputtering technique. In order to investigate the behaviour of the different resonant modes upon deformation, the active AlN films are deliberately grown with their microcrystals tilted with respect to the normal, so that they can to excite both longitudinal and shear modes.

To characterize the electrical behaviour of the SMRs under different strains, the rectangular silicon strips are mounted in a homemade substrate holder that enables to fix their ends and to apply a controllable strain in its back using a micrometre screw fit to a lever (see Figure 1). The silicon strips containing the SMR are first strained to a value close to the maximum deformation achievable before being fractured. Then the resonant frequency of both, the longitudinal and the shear modes are measured with an impedance analyser and tracked as the stress in the silicon strip is gradually released until equilibrium is reached (see Figure 2). Additionally, the frequency response of the SMRs under DC-polarisation is assessed in order to investigate the influence of the different materials apart from the AlN layer. Simulations of the deformation enable to assess the actual stress of the SMRs, given that the stress distribution in the sample is not uniform. In a second measurement, a mean value of the strain in the sample is assessed through a strain gauge glued to the surface of the silicon strip. Preliminary results show that longitudinal modes shift to lower frequencies, opposite to shear modes that shift to higher frequencies as the silicon strip is strained. Theoretical calculations of the strain exerted in the samples are being carried out in order to determine the exact value of the sensor sensitivity.

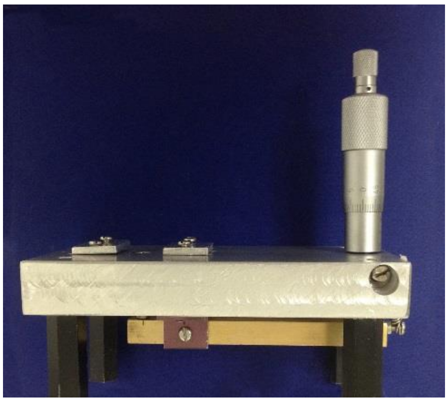

Figure 1: Substrate holder for device deformation

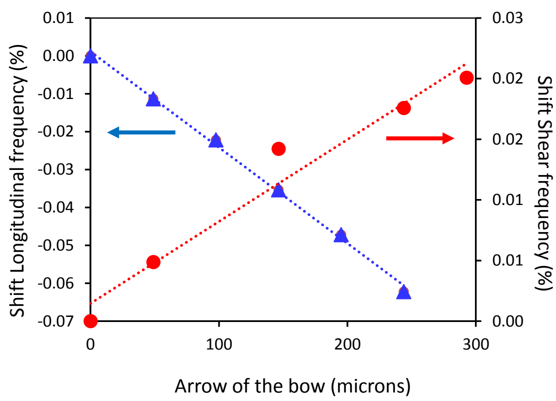


Figure 2: Measured shift of the longitudinal and shear resonant frequencies as a function of the arrow of the bow in the strained silicon strip

# Blackbody-radiation shifts of ytterbium optical lattice clocks

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Recently, the rapid developments of the optical lattice clocks make us concern about the blackbody-radiation (BBR) shift, which is resulted from the residual electric field around the cold atoms. Here we propose a new method for estimating blackbody-radiation shift and uncertainty in the $^{171}$Yb optical lattice clocks by numerically simulating the temperature distribution around the cold ytterbium atoms based on the measured temperatures on the surface of the vacuum chamber.

We measure the temperatures on the outside surface of the vacuum chamber during the whole clock operation process by using seven calibrated temperature sensors. Then we simulate the temperature distribution inside of the vacuum chamber by ANSYS. The temperature gradients around the cold atoms are determined by the non-uniformity of the chamber. We apply the convective heat transfer coefficients of 13 and 200 W/(m$^2$ K) on different parts of the chamber. The atoms absorb the radiation from the inner surface of the chamber with the absorption coefficient of 0.9 (metal chamber) and 0.8 (glass windows). Finally we obtain the temperature distribution through the steady-state analysis around the cold atoms as shown in Fig.1.

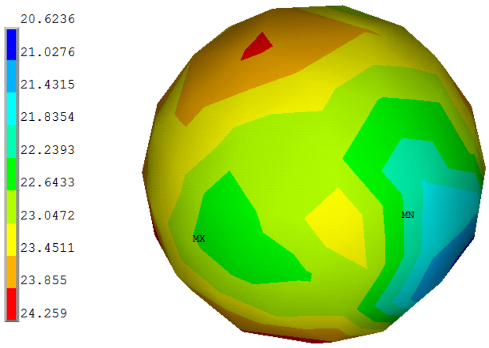


Fig.1: The temperature distribution around the cold atoms inside of the vacuum chamber.

The results show that the largest temperature variation at the center of the ytterbium atomic cloud is 0.43K when the environmental temperature changes from 293.15K to 293.65K around the clock apparatus. The corresponding blackbody-radiation shift is calculated to be -1.246(7) Hz with the uncertainty of $1.42\times10^{-17}$ for our ytterbium optical lattice clock. For comparison, if only using the measured temperatures on the surface of the chamber without the simulation [1], the BBR shift is calculated to be -1.282(7) Hz with the uncertainty of $3.43\times10^{-17}$. Therefore, this new method will be very helpful for precisely evaluating the BBR shift and uncertainty of the optical lattice clocks without the sensors inside the chamber.

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# Ultra-low-noise optoelectronic oscillator at 10 GHz based on a short fiber delay

Lelièvre Oriane[1], Crozatier Vincent[1], Baili Ghaya[1], Berger Perrine[1], Morvan Loïc[1], Pillet Grégoire[1], Dolfi Daniel[1], Llopis Olivier[2], Goldfarb Fabienne[3], Bretenaker Fabien[3]

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We report on an optoelectronic oscillator (OEO) at 10 GHz based on a 1 km long fiber delay, and exhibiting simultaneously an ultra-low close-in phase noise and a low spurious level.

OEOs are known to deliver ultra-low phase noise microwave signals at high frequency with a quite easy setup [1]. As expected from a simple feedback model considering the microwave amplifiers as the main noise source, the phase noise level of an OEO can be reduced by lengthening the fiber delay. But this is true only up to few kilometers, where other noise sources start to dominate, such as the conversion of laser frequency noise to microwave phase noise [2], and nonlinear effects in the fiber [3]. Moreover, a long fiber delay leads to a high level of spurs at multiples of cavity free spectral range, and to a large volume, both criteria being detrimental for demanding applications.

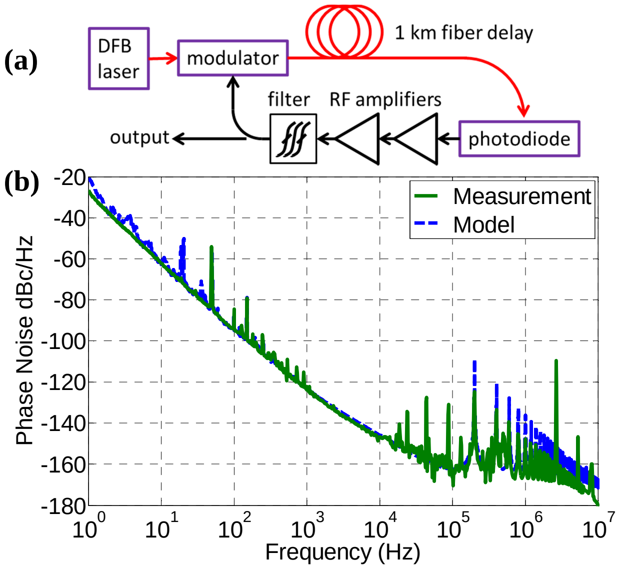


Fig. 1: (a) OEO setup. (b) Phase noise at 10 GHz.

In this work, we use low-noise and high power semiconductor DFB laser driven by a low-noise current source, a low-Vpi modulator, ultra-low phase noise RF amplifiers, and a custom RF filter based on a high Q-factor dielectric resonator. An ultra-low close-in phase noise (-94 dBc/Hz @100 Hz) and a low spurious level (below -110 dBc/Hz) are then obtained with only 1 km of fiber (Fig. 1.b). These performances are well predicted by a model adapted from [2] and feed by actual frequency and intensity noises of the laser source, that are the limiting phenomena for the close to the carrier phase noise and spurs level, respectively. To the best of our knowledge, these noise and spurs level are the lowest for such a short delay, these performances exceeding the ones of OEOs using up to 4 km fiber length.

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# GNSS Disciplined Oscillators: an approach based on real-time steering over the Internet with certification

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GPS Disciplined Oscillators (GPSDOs) serve as an indispensable source of timing in a range of applications, belonging both to the scientific and industrial contexts. GPSDOs based on the Common-View approach (local oscillator is disciplined to a reference time scale through the use of Common-View satellite observations) have already been proposed and implemented [1]. In this work, we propose another system architecture: the local oscillators will be slaved to a remote reference time scale by means of time and frequency corrections streamed over the Internet in real time.

Fig. 1 shows the elements composing this system. The Time Reference Facility (TRF) includes a calibrated GNSS receiver synchronized to a reference time scale, typically a local realization of UTC (i.e. UTC(k)). In parallel, the User Terminal (UT) includes a calibrated GNSS receiver connected to the local oscillator to be disciplined, typically a Rubidium Atomic Frequency Standard (RAFS). UT and TRF receivers broadcast real-time GNSS observations to the Time Signal Generator (TSG) – to be intended as a processing server – in the NTRIP ('Networked Transport of RTCM via Internet Protocol') format. Common-View algorithm is operated in real time at the TSG level to obtain the time offset between the TRF and UT reference clocks, which is then streamed to the UT managing system in real time through a secure internet link. A Proportional-Integral-Derivative (PID) algorithm is there implemented to obtain the steering corrections, required to physically discipline the Rubidium oscillator, from the time offset data. Furthermore, the measured time offsets (TRF-UT) are used to issue a certificate to the user, giving the time and frequency offset of the local oscillator with respect to the TRF reference time scale. If such a reference time scale is a local realization of UTC, the certification allows the user to trace its clock to UTC.

*This work is part of the DEMETRA project which received funding from the European GNSS Agency under the European Union's Horizon 2020 research and innovation programme under grant agreement No 640658.*

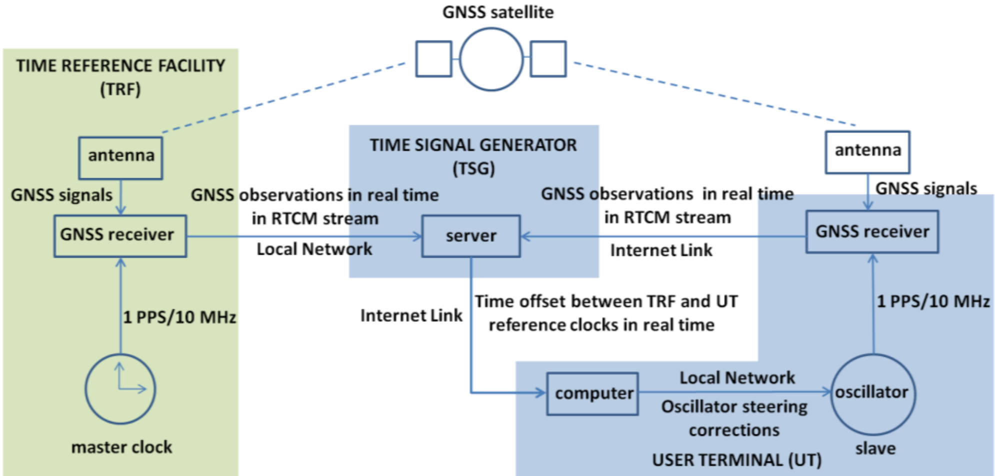


Fig. 1. Block diagram of the proposed common-view disciplined oscillator system

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# Build-Up Detection and Level Monitoring by Using Capacitive Glocal Technique

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This paper presents an innovative proof of concept of level monitoring capacitive sensor and build-up detection by using the "Glocal" (global and local) E-fields. The change in the sensitivity of the sensor to detect the build-up on the sensor probe is increased by using local E-fields. An initial prototype sensor with the length of 89.5 mm is developed and tested on various fluids. Finite element method (FEM) analysis is also performed in order to investigate the sensitivity of the proposed sensor in different liquids with various dielectric constants. An analytical model is also presented which estimates the electric field strength between the capacitive elements as a function of level for a single segment.

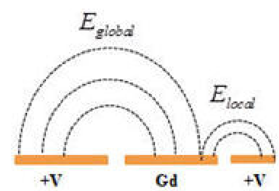


Fig. 1: Concept of Glocal E-fields

Precision and accuracy of capacitive level sensor (CLS) is drastically reduced due to build-up or coating problem. The copper plates having a less distance between them, creates strong local E-fields (confine field) which can detect the effect of build-up or coating problem as shown in fig. 1. On the other hand, global E-fields generate by the large distances between the copper plates for level monitoring. The advantage of the developed CLS is to investigate fluid level as well as the coating problem just by Cu-strips instead of adding any other electronic circuits like others. The most important benefit of then presented sensor is that it is economical, easily manufacturable as compare to other fluid level approaches (contact and contactless methods) [1].

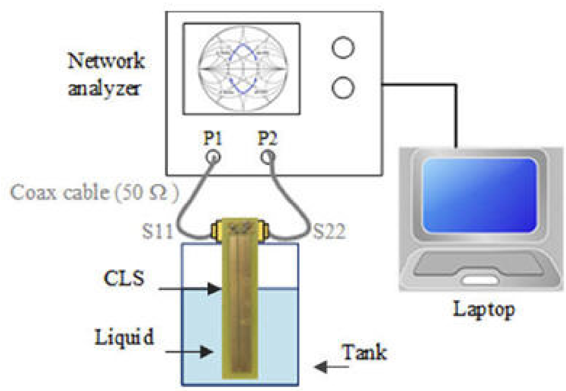


Fig. 2: Measurement setup

The measurements were conducted using a vector analyzer (Agilent 8753ES) by applying the frequency sweep of 0.3 MHz to 20 MHz as shown in fig. 2. The global and local capacitances were extracted from the measured data (S11 and S22) of vector analyzer by using Z-plots at 1 MHz. Several measurements were performed with and without insulating material. In the end, different thickness of parafilm'M' ($\varepsilon_r = 2.3$) are used to detect the build-up effect. Under the all circumstances, sensitivity is examined in different dielectric constant of liquid.

Within the presented work, single segment based capacitive sensor is successfully developed to detect the build-up effect by incorporating local E-fields and global E-fields for level monitoring. In addition, future development is to implement a multi-segments based CLS.

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# Planar Angle Metrology: The INRIM - INFN Ring Laser Gyroscope

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Ring lasers gyroscopes exploit the Sagnac effect for providing inertial measurements of rotation rate. The rotational motion of their reference frame determines a differential frequency shift (Sagnac frequency) between the two oppositely travelling beams generated inside the optical cavity. For a ring cavity of area vector **A**, perimeter $P$ and an emission wavelength $\lambda$, this frequency is

$$f = \frac{4}{\lambda P}\mathbf{A}\cdot\mathbf{\Omega}$$

being $\mathbf{\Omega}$ the angular velocity vector of the cavity frame. Laser gyroscopes with perimeter-length of tens of centimetres are commonly used for inertial navigation applications while larger systems (side-length larger than one meter), rigidly fixed to the ground, provide precise measurements of the Earth rotation rate and of the small superimposed local rotations coming from geophysical and geodetic phenomena.

Applications of RLGs in Angular Metrology have been foreseen since the end '60s. The basic idea is to use the interference fringes by the two counter propagating modes as an ultra-fine angular scale dividing the full angle into a number $N=P/\lambda$ intervals. The most effective realization of such kind of goniometer is the ring laser developed by Yu. V. Filatov and collaborators since the end of 70s, consisting in a monolithic cavity 11 cm in side-length equipped with total reflection prisms in optical contact with a Zerodur cavity frame [1]. The typical resolution of these systems is at the level of 100 nrad, typically limited by the errors due to the influence of environmental parameters on the ring laser dynamics.

In a collaboration between INRIM and INFN, we are presently building a new kind of laser goniometer with a target accuracy is 10 nrad, being the accuracy of the most precise angular encoders at the level of some 100 nrad in spite of a resolution more than one order of magnitude better. Our project foresees a square non-monolithic cavity of 0.50 m in side, making use of the last generation dielectric super-mirrors employed in the larger gyroscopes for geodetic and geophysical applications. The laser cavity is mounted on a rotating platform and is equipped with a nanometric mirror positioning system allowing an accurate control of the ring laser parameters. The system is presently in the phase of assembling.

We will discuss the main issues and proposed strategies concerning the implementation of an extremely accurate transportable rotational standard, the realization of a very sensitive gyroscope for the measurement of seismic effects, the demonstration of a self-calibration concept leading to the design of a larger rotating RLG for geodetic and relativistic experiments.

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# Optimized 1f-2f Actively Compensated Frequency Synchronization

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To satisfy the Square Kilometre Array (SKA) radio telescope requirements on frequency synchronization, we proposed a 1f-2f actively compensated frequency synchronization system with phase noise compensation function placed at the receiving site (RX) [1]. Based on it, we designed a prototype module [2]. In September 2015, the prototype module was shipped to SKA South Africa site to perform a trial test on the site's overhead fiber links. From the test results, we found that there is a bump on the Allan variance plots of dissemination stability at the averaging time between 10s and 100s. After that, we simulated the desert's temperature variation and repeated experiments in our lab and found that the dissemination stability of the system was affected by ambient temperature variation of fiber link. It means that our frequency dissemination system cannot completely compensate the phase fluctuation induced during fiber dissemination. We found it is caused by the nonlinear effect of RF components in the system. More specifically, the 1f-2f relationship of two RF frequency signals (1GHz and 2 GHz) enhance the nonlinear effects of frequency mixer. The nonlinear effect will cause the periodic fluctuation of error signal, and its period is related to the temperature variation speed of fiber link. Consequently, we optimized the 1f-2f frequency synchronization scheme. In the optimized scheme (Fig.1), the transmitting site (TX) is almost the same as that of [1]. At RX, the 1 GHz PDRO was replaced by PDRO2 and PDRO3 (with frequencies of 1 GHz+100Hz and 1 GHz-100Hz, respectively) which are phase locked to the same OCXO.

We perform a comparing test of the original and optimized schemes on 50 km fibre spool which is placed in a temperature-controlled box. The temperature of the box is controlled to change 10 degrees per hour. In the optimized scheme, the bump on the Allan variance plot almost diminished.

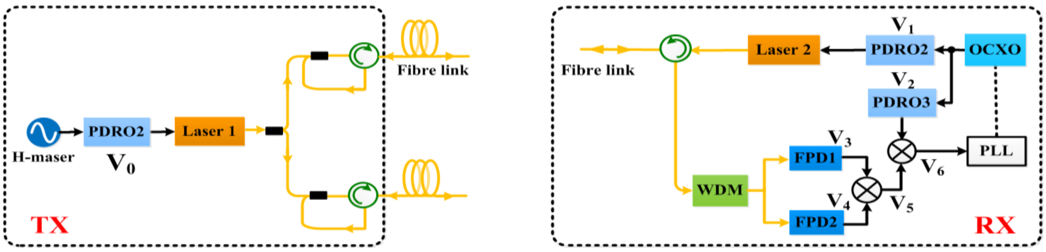


Fig. 1: Schematic diagram of the amended actively compensated frequency dissemination system

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# Calculation of Quadratic Zeeman Shift by Regularization Method for an Atomic Fountain Clock KRISS-F1

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The evaluation of the quadratic Zeeman shift requires the information of magnetic field distribution along the drift region in atomic fountain frequency standards [1]. Zeeman frequencies against various launching heights provide the averaged magnetic field distribution seen by the atoms. Using those data, we were able to deduce a reasonable field map with an approach of solving an inverse problem. In order to establish the linear simultaneous equations for our problem, we start with the integral transform equation as below:

$$\bar{B}(h) = \int_0^h w(h,z)B(z)dz, \quad w(h,z) = \frac{1}{2\sqrt{h(h-z)}}, \tag{1}$$

where $B(z)$ is the magnetic field strength at position $z$, $w(h,z)$ is the weighting factor proportional to the reciprocal of the atomic velocity, and $\bar{B}(h)$ is average magnetic field seen by the atom whose apogee is at height $h$. Equation (1) can be discretized as $\bar{B}_i = \sum_j w_{ij}B_j$ with a tricky method preventing $w_{ij}$ from diverging at $z = h$. After making a matrix form $\bar{\mathbf{B}} = \mathbf{WB}$, we can solve it straightforwardly with Tikhonov Regularization method:

$$\mathbf{B} = \arg\min[\|\mathbf{WB} - \bar{\mathbf{B}}\|^2 + \lambda\|\mathbf{LB}\|^2] = (\mathbf{W}^t\mathbf{W} + \lambda\mathbf{L}^t\mathbf{L})^{-1}\,\mathbf{W}^t\bar{\mathbf{B}} \tag{2}$$

where $\mathbf{L}$ is an operator that measures the irregularity of its operand, and $\lambda$ is for controlling the strength of regularization. Figure 1 shows the calculation results (refer to figure caption). Relative uncertainty due to the spatial inhomogeneity was estimated to be less than $10^{-18}$ from the field map. Detailed explanation about the calculation will be given at the conference.

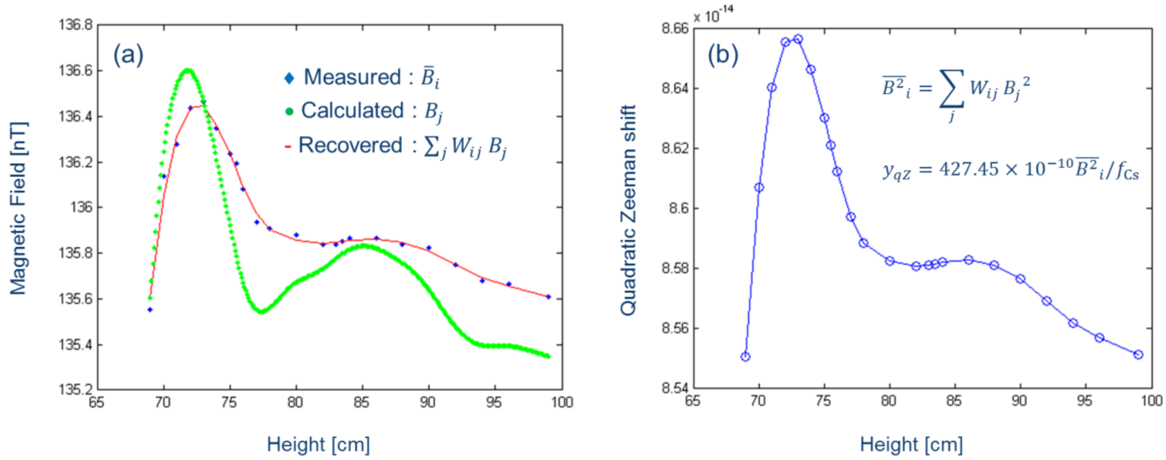


Fig. 1: (a) Magnetic field distribution (circle) along the drift region calculated from average values (rhombus) for various launching heights, (b) Calculation of quadratic Zeeman shift using the magnetic field map.

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# Very High Sensitivity Laser Gyroscope for General Relativity Tests in a Ground Laboratory

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The Gross Ring G is a square ring laser gyroscope, built as a monolithic Zerodur structure with 4 m length on all sides. It operates at 632.8 nm and is excited by a helium-neon radiofrequency discharge. G has demonstrated that a ring laser has a sensitivity high enough to measure the Earth rotation rate with a precision of $\Delta\Omega_E < 3\cdot10^{-9}$. It can provide a local measurement of the Earth rotation rate with a sensitivity near to that provided by the international system IERS. Furthermore it is possible to show that further improvement in sensitivity could allow the observation of the metric frame dragging, produced by the Earth rotating mass (Lense-Thirring effect), as predicted by General Relativity. The GINGER project is intending to take this level of sensitivity further and to improve the long-term stability. This result should be obtained by enlarging the ring dimension and by using top-in-art very low loss mirrors.

A monolithic structure similar to the G ring laser is not available for GINGER. Therefore a preliminary goal was to define a procedure to achieve the necessary mechanical stability through an active control of the optical cavity geometry [1,2]. This procedure is under test on a square gyroscope of 1.65 m of side (GP-2) that has been assembled inside the INFN laboratories in Pisa. An important step to achieve optimized sensitivity is also the study of the role of the active medium gain distribution inside the discharge capillary in order to obtain stable single mode TEM00 laser emission without introducing additional losses.

The site where the GINGER apparatus would be located, should be well isolated from surface meteorological and seismic noise. The INFN Gran Sasso underground laboratory, beneath more than 1000 meters of rock in the Apennine mountains could be suitable for this purpose. With the aim of verifying the noise quality of the site, in view of an installation of a future GINGER apparatus, we have installed there a second ring laser, 3.6 m in side length (named GINGERino) that is presently operating as a seismic station.

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# Optical phase locking of DBR laser for atomic gravimeter

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Optical phase locking (OPL) of near infrared diode lasers can be widely used for atom interferometry [1], and CPT clock [2] using the ground hyperfine splitting of Cs and Rb atom. The residual phase noise of the dedicated OPL system with extended-cavity diode lasers (ECDLs) is much lower than the ultra-low phase noise crystal oscillator for certain Fourier frequency range [3]. Therefore total absolute phase noise of the OPL system with ECDLs is dominated by the local oscillator. The OPL system based on ECDLs is adequate for ultra-high performance atom interferometry, and CPT clock. However the ECDL OPL system is not robust enough to operate it in the harsh environment, since the frequency of ECDL is very sensitive to operating environments such as pressure, temperature, humidity, acoustic and vibration noise. DBR (Distributed Bragg Reflector) and DFB (Distributed Feedback) lasers are much stronger than the ECDLs in the same environmental condition.

We perform OPL of two DBR lasers to be used for an Rb atomic gravimeter developing at KRISS. The residual phase noise of DBR laser OPL is higher than that of ECDL OPL for same OPL loop bandwidth, because the linewidth of the DBR laser is broader than the ECDL. The Fig. 1 shows the beat spectrum of two optical phase locked DBR lasers. Frequency difference of two lasers is 6.9 GHz which is the frequency near $^{87}Rb$ ground hyperfine splitting. The OPL loop bandwidth is approximately 10 MHz, and the integrated phase variance $\sigma_\varphi^2$ is 0.29 rad$^2$. We calculate sensitivity limit of atomic gravimeter using the measured phase noise of DBR laser OPL system. Currently the ECDL OPL system is being used for Rb atomic gravimeter [3]. If we introduce this DBR laser OPL system, sensitivity of atomic gravimeter would be similar or still lower than effect of local oscillator phase noise on the sensitivity of gravimeter depending on the duration and interval of Raman pulses.

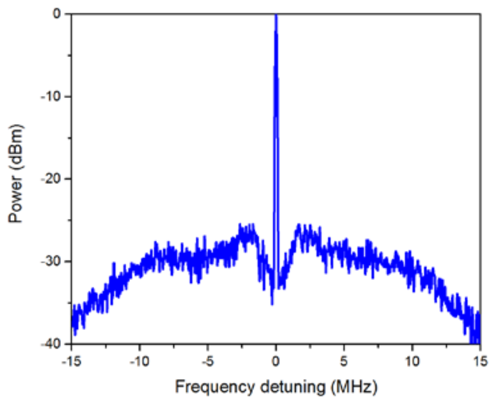


Fig. 1: Beat spectrum of optically phase locked two DBR lasers. Center frequency of beat spectrum is 6.9 GHz. Resolution bandwidth is 100 KHz.

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# Optical quenching of bosonic magnesium

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We report on the progress towards optical quenching of the narrow $3^1S_0 \rightarrow 3^3P_1$ intercombination line in $^{24}$Mg [1]. The two-photon process couples the $3^3P_1$ state to the energetically higher state $4^1S_0$, followed by spontaneous decay to the $3^1S_0$ ground state. This gives rise to a quasi two-level-system with faster decay rate of the $3^3P_1$ state, adjusted via the quench laser intensity at 462 nm. With this technique applied to optically trapped magnesium atoms, we expect to demonstrate cooling temperatures of a few µK.

So far, we prepare $10^5$ atoms with a temperature of 100 µK in the $^3P_0$ state using a continuous loading scheme for an optical dipole trap (ODT) at 1064 nm [2]. Subsequently, the atoms are optically pumped back to the $3^1S_0$ ground state and transferred to the magic wavelength optical lattice [3]. The quenching-assisted cooling scheme could look as follows: (1) Atoms are excited on the first red sideband of the $3^1S_0 \rightarrow 3^3P_1$ transition at 457 nm, (2) the quench laser optically pumps the atoms to the $4^1S_0$ state along the lattice axis and (3) the atoms decay fastly via $4^1S_0 \rightarrow 3^1P_1 \rightarrow 3^1S_0$ back to the $3^1S_0$ ground state.

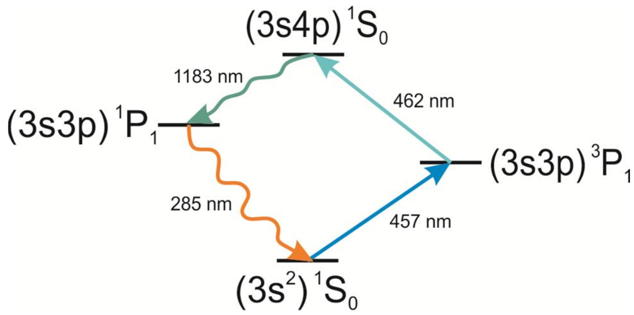


Fig. 1: Relevant transitions for quenching of $^{24}$Mg.

An alternative cooling mechanism would be given by a novel scheme of Sisyphus cooling [4]. Here, the differential AC -Stark shift imposed by the ODT on the $3^1S_0 \rightarrow 3^3P_1$ transition makes excited state atoms interact with a steeper potential than those being in the ground state. Spontaneous decay after laser excitation, which is enhanced by means of the quenching laser, induces on average a net loss of kinetic energy.

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# VNIIFTRI Primary Frequency Standard: Current Status

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National Frequency Standard of Russia, SU-CsFO2, has been in use since 2012 [1]. CsF02 is used for the local representation of the UTC maintained by SU. To date, 18 calibrations of the International Atomic Time (TAI) have been reported to BIPM with a relative frequency agreement of $(-0.7 \pm 4.5) \cdot 10^{-16}$, between CsFO2 and the average of the other fountains operated in the world in the reference periods.

Accuracy evaluations have enabled its type B uncertainty to be reduced to $2.5 \cdot 10^{-16}$, taking into account improved evaluation of the microwave power dependence shift, the distributed cavity phase shift and collision shift. Our conference paper will update our progress towards the SU-CsFO2 accuracy evaluation.

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# A Rotating Fan-Beam Radiation Model for the Pulse Duration and Frequency Spectrum of Pulsar Radiation

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The assumption of a rotating fan beam of broadband RF radiation would appear to give a good fit to the observed pulse length to period ratio and pulse amplitude statistics of some pulsars. The radiation pattern is assumed to arise from standing waves in multiple radiating layers of (ionospheric) plasma above and around the equator of the pulsar. The plasma carries current which creates the magnetic poles of the pulsar. The particle beams emitted from the poles act as a *secondary* radiator for the pulse radiation generated by the equatorial layer currents. In this model the radiation is not directed along the spin axis but is at right angles to it. The frequencies of the multiple layers form a comb spectrum with components spaced at the pulsar rotation frequency. The pulse length to period ratio is found to be inversely proportional to the number layers, typically being about 40 in number. The model is based on measurements made on spinning cylinders reported in [1]and [2] and layered surface waves reported in [3] and [4].

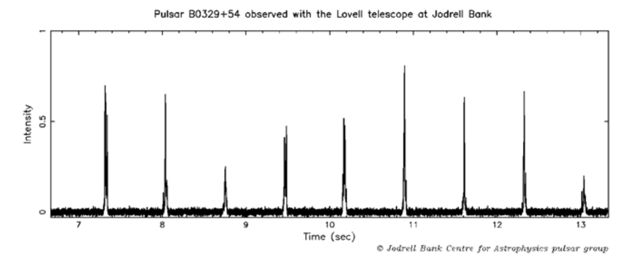


Fig. 1: Sequence of received pulses from Pulsar BB0329+54 observed with the Lovell telescope at Jodrell Bank. Intensity versus time (sec)

Figure 1 shows nine pulses from a Pulsar BB0329+54 observed with the Lovell telescope at Jodrell Bank at a VHF frequency [5]. Such records present measured pulse width and amplitude statistics of radiation from a given pulsar. Figure 2 shows the kind of fan radiation pattern generated by the combination of the multiple plasma layers. Four angles of rotation about a vertical axis are shown. The proposed radiation model can have its parameters adjusted to fit the data for a given pulsar.

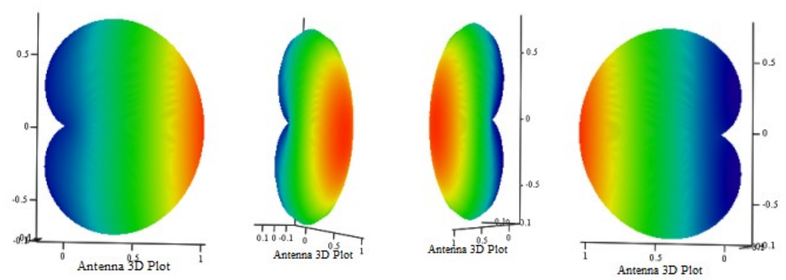


Fig. 2: Sequence of rotating fan beam radiation from a pulsar spinning on a vertical axis

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# Sequential measurement of optical frequency difference of semiconductor lasers for time transfer system


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The stability and accuracy of optical time transfer system (OTTS) depends, among other factors, on optical frequency difference between forward and backward direction laser transmitters [1]. The OTTS system exploits two lasers working in two different ITU channels and their optical frequency difference is 100 GHz (0,8 nm). In principle, measurement of optical frequency difference could be made using typical optical spectrum analyzer (OSA), but its resolution and accuracy is insufficient in this application. This paper describes the concept of precise measuring the difference of optical frequency of two semiconductor lasers spaced 100 GHz apart and more. The idea of measuring is presented in Fig 1. This method exploits two

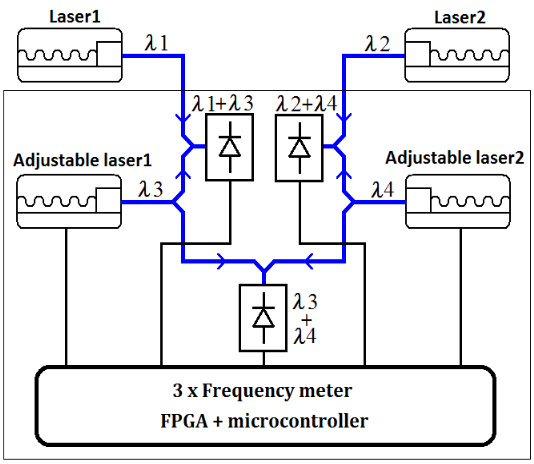


Fig. 1: An idea of measuring the difference of semiconductor lasers carrier frequencies using beatnote signal and two auxiliary adjustable semiconductor lasers.

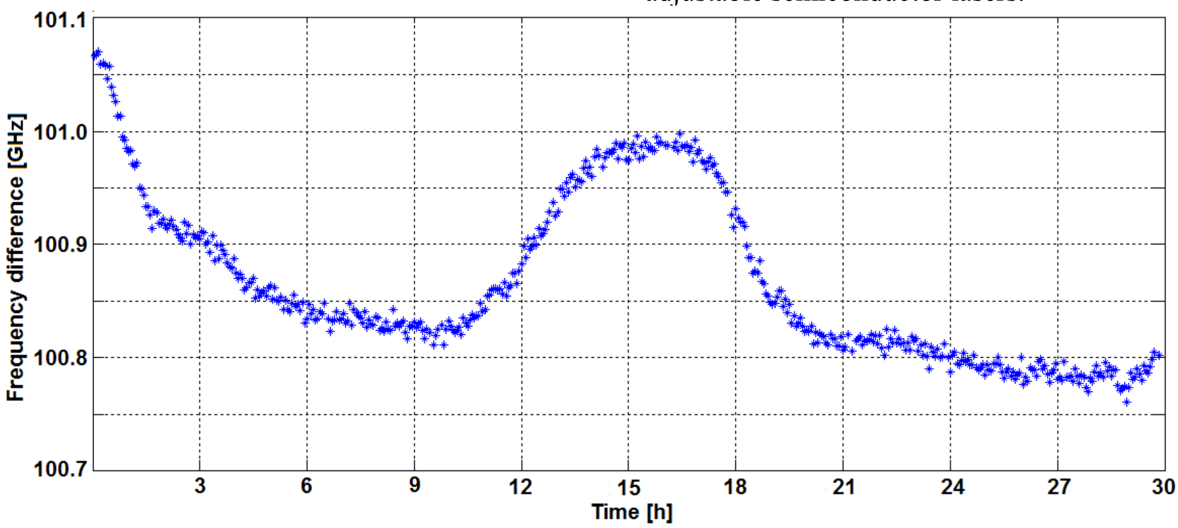


Fig. 2: The record of a day measurements of frequency difference of two DFB lasers.

auxiliary adjustable semiconductor lasers and three high-speed photodiodes. Single measurement consists of several steps. During measurement adjustable lasers change sequentially wavelengths and beatnote signals from three photodiodes are recorded. Final result of measurement of optical frequency difference between two lasers is a sum of partial measurements of frequency from three photodiodes. An example of a day measurements showing the relative stability of two DFB lasers is presented in Fig 2.

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# Direct Comparison of Two Optical Cryogenic Silicon Resonators

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Owing to their outstanding mechanical and thermal properties, single-crystal materials have proven to be an ideal choice for ultra-stable optical resonators. Among them, silicon has been demonstrated to be a good choice for achieving a stabilized laser with a narrow linewidth [1] and good long-term stability [2].

Improving on the design of our first-generation crystalline-silicon resonator, we have set up two identical systems with the goal of reaching the thermal noise floor of $5 \times 10^{-17}$ determined by the Brownian noise in the high-reflectivity dielectric coating at a temperature of 124 K. The side-by-side comparison of the two systems allows us to identify the remaining sources of instability and accurately measure their effects on the laser frequency.

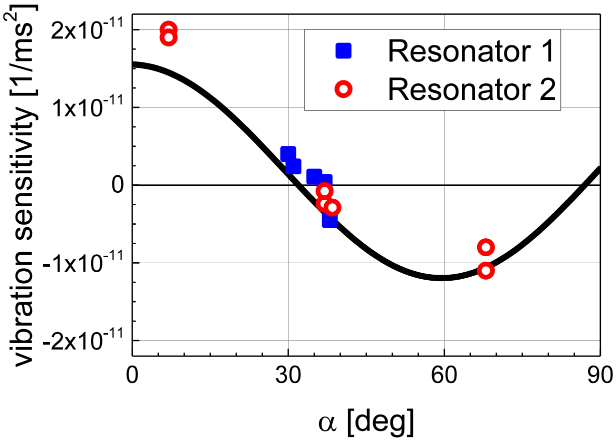


Fig. 1: Vertical acceleration sensitivity of the silicon resonator as a function of the angle α around its vertical axis. (symbols: experimental data; continuous line: FEM simulation)

We discuss the impact of seismic perturbations on the resonator, and its reduction using a specially designed tripod cavity support structure incorporating the anisotropy of the single-crystal silicon (Fig. 1). The effect of pressure fluctuations is measured and translated to frequency instability. Employing the scheme from [3], the residual amplitude modulation on the laser is maintained at a sufficiently low level. The frequency instability induced by temperature fluctuations and laser power fluctuations are also discussed.

A highly stable room-temperature ULE resonator [4] in a three-cornered-hat comparison can be used to unambiguously determine the performance of each of the two systems.

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# Behavior of Quartz Crystal Resonators at Liquid Helium Temperature

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Quartz crystal resonators working at liquid helium temperature are an exciting topic of interest. Indeed, high quality devices can exhibit quality factors of a few hundreds of millions, from tens of megahertz to hundreds of megahertz, and can reach a few billions for the best ones. As a consequence they are good candidates to various applications ranging from frequency references to fundamental physics.

A brief reminder is first provided regarding quality-factor properties of, mainly, Bulk Acoustic Wave SC-cut resonators within the temperature range 3K - 12K [1-2]. The A, B and C mode behaviors are also examined in terms of frequency versus temperature. As unpublished data, the frequency dependence with the excitation power is particularly highlighted. Finally recent measurements on noise are discussed [3].

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# Towards an Engineering Model of Optical Space Cs Clock

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The optical pumping of the Cs hyperfine state was identified many years ago as a suitable technology candidate for an atomic clock to operate in GNSS, and in particular in Galileo. Related industrial activities currently develop this technology with focus on ground applications [1, 2]. Based on their heritage in the domains of Cs clock development and space electronics, Thales Electron Devices and RUAG develop the engineering model (EM) of the Optical Space Cs Clock (OSCC). The current project phase started in 2015 and will end in 2017.

In the previous phase, a short-term frequency stability of $3E\text{-}12\tau^{-1/2}$ was demonstrated. The target of the present phase is $1E\text{-}12\tau^{-1/2}$. In addition, new design constraints are taken into account: 12 liter volume, 10kg mass, 30W power consumption and 12 years lifetime in medium earth orbit.

After a presentation of the main activity objectives, the paper will describe details of the preliminary design. First, clock operation using a new optical isolator free optical subsystem prototype will be reported. Second, exhaustive comparative test results from the evaluation of new laser diode sources with reduced linewidth from III-V Lab will be shown. The sources address the Cs D1 and D2 transitions [2, 3]. Third, the constraints rising from a potential space-operation of the laser diode and the photodiode will be described. The status of the respective space evaluation will be reported.

This development is supported by the European Space Agency under European GNSS Evolutions Programme (activity ID-98) and CNES under contract n° 150920.

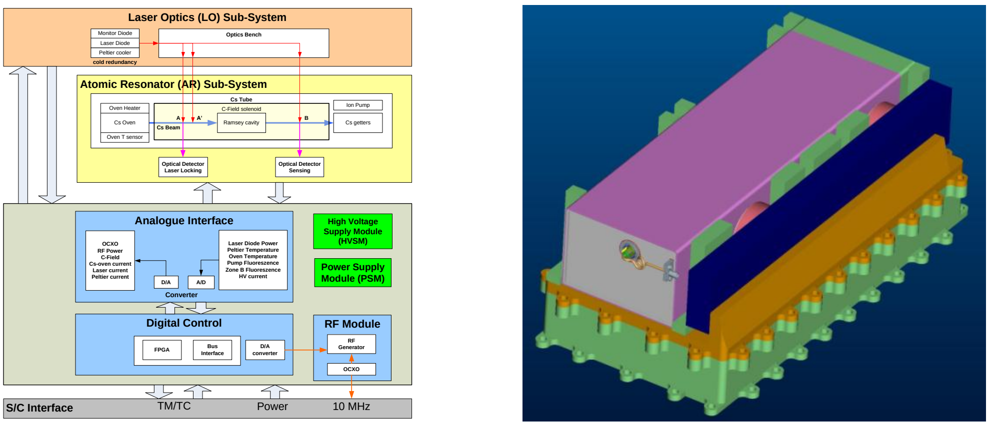


**Figure 1:** *Left:* Functional architecture of the OSCC EM. *Right:* Preliminary design of the physical implementation.

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# The optical feedback spatial phase driving perturbations of DFB laser diodes in an optical clock

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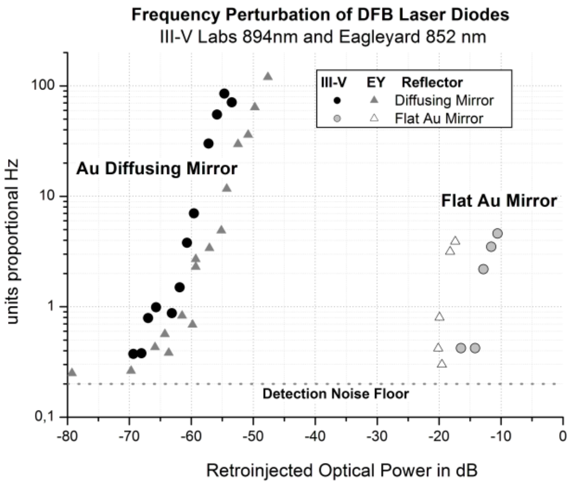
The impact of low level feedback into DFB laser diodes has been studied intensively since more than three decades [1]. Here, the so far not considered spatial phase profile of back-reflections is identified as a key driver for the perturbation strength. Practical impacts to optical clock design are described.

Any optical clock is based on the detection of an atomic fluorescence or absorption intensity signal. A stable laser operation in frequency and optical band power is a pre-requisite for stable clock operation. Back-reflection into DFB lasers induces mode competition [2] and the self-mixing phenomenon [3]. Both perturb either the free running optical frequency or the band power if the carrier frequency is locked. To avoid laser diode perturbation, unwanted feedback from optical systems is typically attenuated by up to 60dB using optical isolation. As an example case it will be reported how residual reflection from an optical isolator can still perturb the operation of an optically pumped Cs clock [4] upon nm position drifts.

To characterize the optical frequency shift due to feedback from a position modulated, piezo-mounted mirror, the out-of-feedback bandwidth error signal of the laser diode frequency lock is used. DFB laser diodes from Eagleyard and III-V Lab [5] are compared with respect to their feedback sensitivity (see Figure 1). The feedback levels down to -70dB are considered. It turns out that the spatial phase distribution of the reflected beam (induced by a particular roughness profile of the reflecting surface) changes the impact of a given feedback intensity by up to 4 orders of magnitude.




In conclusion, even lowest levels of back-reflections significantly perturb laser diode operation and optical clock performance if the reflections phase profile is inhomogeneous and if the reflection geometry changes slightly (due to e.g. thermal drifts in the setup). Exhaustive results of ongoing measurements regarding for example the perturbation scaling with the roughness of the reflecting surface and on the carrier band power perturbation will be presented. Impacts on the stability of the optically pumped Cs clock will be discussed.

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# New insights on the determination of the linewidth of low-noise signals with the emergence of a coherent peak

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Stable and narrow-linewidth lasers required in many applications are typically achieved by stabilization to a high-finesse optical cavity or by phase-locking to another stable oscillator. The frequency-noise power spectral density (FN-PSD) fully characterizes the noise properties of a laser. However, laser experimentalists often prefer the notion of linewidth, which constitutes a single and convenient parameter to compare lasers. The concept of the $\beta$-separation line introduced by Di Domenico *et al*. provides a simple approximation of the linewidth corresponding to an arbitrary FN-PSD [1], which does not require computing the exact, complicated and time-consuming formula that links the FN-PSD to the laser linewidth [2]. This approximation proved to be valid for experimental linewidths ranging from kHz to MHz [3] and is thus being widely used by experimentalists in the field of stabilized lasers. According to this concept, the linewidth collapses to zero when the entire FN-PSD becomes lower than the $\beta$-separation line, which corresponds to a tight lock characterized by the presence of a coherent peak in the center of the spectrum.

However, this approximate linewidth becomes imprecise when the FN-PSD approaches the $\beta$-separation line. In the present work, we investigate in more details the transition occurring from a finite linewidth to a coherent peak. We performed both simulations and experimental verification measurements with different types of frequency noise spectra (e.g., band-pass filtered white noise and real noise from an optical frequency comb) to study this transition. Our results show that the integrated phase noise $\Delta\varphi_{rms}$ is the relevant parameter to describe the occurrence of a coherent peak, which can be achieved even if the FN-PSD exceeds the $\beta$-separation line and $\Delta\varphi_{rms} > 1$ rad. Fig. 1 displays some experimental results showing the transition between a finite linewidth and a coherent peak obtained for a real signal from a frequency comb, which will be complemented by additional simulations and experiments. As a result of these investigations, the crossing point of the FN-PSD of the free-running oscillator with the $\beta$-separation line gives a conservative estimation of the feedback bandwidth that is required to achieve a tight lock in a stabilization loop.

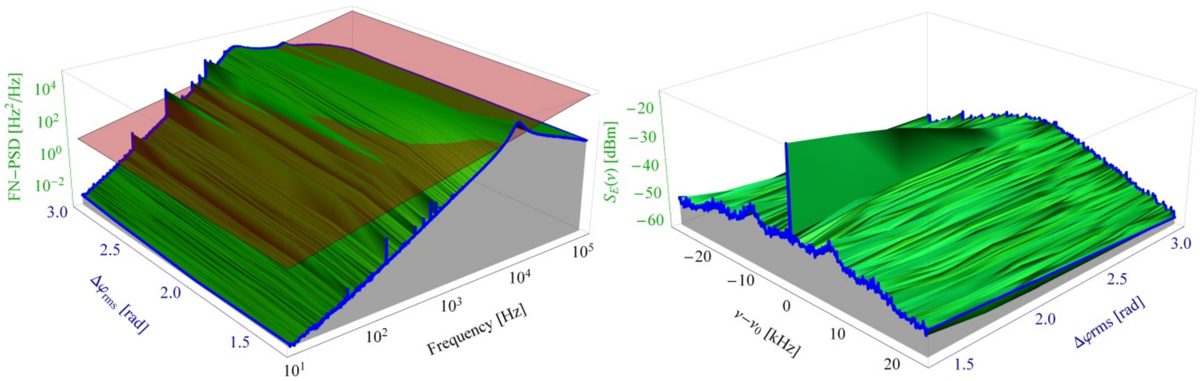


Fig.1: [Left] Experimental FN-PSD of the carrier-envelope offset beat in a frequency comb at different gains of the stabilization loop, i.e., with different integrated phase noise $\Delta\varphi_{rms}$. The red surface corresponds to the $\beta$-separation line. [Right] Power spectrum $S_E(\nu)$ measured for the corresponding conditions. The transition between a finite linewidth and a zero linewidth signal with a strong coherent peak occurs for $\Delta\varphi_{rms} > 1$.

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# Iodine Absorption Cells Quality Measurements

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This work is oriented to comparison of methods for iodine absorption cells quality evaluation. Optical frequency references based on molecular iodine represent one of the most used references for stabilizion of laser standards working at visible spectral range. Molecular iodine media offers rich spectra of strong and ultra-narrow absortion lines, but it is also a media with very high sensitivity for contamination (contaminants cause frequency shifts of the absorption spectra and degradation of reachable frequency stability of the laser standard) – the chemical purity of iodine cells must be precisellly controlled. Traditional methods for iodine cells quality checking is laser induced fluorescence method (LIF) and absolute frequency shifts measurements [1,2]. Both of these methods have few disadvantages. Frequency shifts measurements need relatively complicated optical setup with precise control of hardly controllable parameters, the LIF measurements depend on design of the cell (suppression of straigh light signals) and normally need quite rare laser wavelength (502 nm), where the effect of collisional quenching is high. Due to this reasons we propose an alternative method of spectral linewidths measurement, which overcomes these difficulties of traditionally used approaches and which serves as a tool for iodine cells quality evaluation. As this method shows a very high sensitivity for the iodine contamination, it can be considered not only for iodine hyperfine spectra scanning (estimation of new transitions suitable for laser standards frequency stabilizations) but it can be used as a evaluation tool in cases where the traditional methods for the cells quality measurements reach their limits [3]. In this linewidth measurements approach the hyperfine spectra of the iodine is precisellly scanned and the linewidth of the selected transition is computed and compared to the value obtained by theoretical computation. In this work we present the results of comparison of two laser induced fluorescence setups (with and without the compensation for the laser source spectral mode-hops) with proposed method of selected hyperfine absorption spectra linewidth measurments and we discuss advantages and limitations of these methods for practical using. A set of iodine absorption cells of different opto-mechanical designs developed and manufactured at ISI and BIPM institutes were precisellly measured by LIF and linewidth systems and these results where used for finding a dependecies between both methods.

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# Operational strontium optical lattice clocks

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Over the last years, optical lattice clocks (OLCs) have become the most stable frequency standards, with frequency instabilities in the low $10^{-16}$ in relative units after 1s of integration [1,2], and a control of systematic effects in the $10^{-18}$ range have been demonstrated [1-3]

LNE-SYRTE has developed two strontium optical lattice clocks, which showed the first agreement between two optical lattice clocks with a total uncertainty exceeding the accuracy of primary frequency standards [4]. On the other hand, the added complexity of OLCs, mainly associated with the large number of laser sources operated at the same time, has raised concerns on their ability to ever replace the well established cesium standards, including atomic fountain clocks. Indeed, practically realizing the SI second requires that several primary standards are in almost continuous operation worldwide. While OLCs have been demonstrated in many metrology laboratories, only sporadic operation has been reported so far. In this context, linking optical clock to international time scales requires extrapolation algorithms to fill the gaps in the operation of optical clocks. The fluctuations of the local oscillator realizing the time-scale -- so far an H-maser -- during these gaps therefore remains the main source of uncertainty.

Here, we report a step forward in the direction of practical optical frequency standards by demonstrating that an OLC using strontium atoms, with an accuracy of $4.1\times10^{-17}$ can be reliably operated over time periods of several weeks, with a time coverage larger than 80%, which can be considered as nearly continuous, given the stability of local oscillators. We take advantage of these long integration times to compare one of our strontium clocks with two atomic fountains with a statistical uncertainty below $10^{-16}$.

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# Robustness testing of a compact auxiliary laser for an optical atomic clock under space conditions

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In the frame of the European project SOC-2 (Space Optical Clock, http://www.soc2.eu), Leibnitz Universität Hannover has developed several compact external cavity diode lasers (ECDL) at different wavelengths as depicted in Fig. 1. These ECDLs serve as auxiliary lasers in optical atomic clocks, for instance a 399-nm cooling laser for an Yb lattice clock or a 689-nm second-stage cooling laser for a Sr clock.

In view of the future development of a space optical clock that is foreseen by the SOC-2 consortium, it is important to evaluate the suitability of this laser technology in space-relevant conditions. For this purpose, an improved vacuum-compatible ECDL prototype at 689-nm has been built and tested in representative thermal-vacuum conditions as well as under characteristic radiation levels. The environmental conditions of the International Space Station (ISS) have been considered as a relevant environment for these tests since the ISS constitutes one of the targeted deployment locations for a space optical clock. Hence, the ECDL was placed in a thermal-vacuum chamber and was subjected to a series of temperature cycles between 10°C and 35°C with a period of 90 min that simulate the ISS thermal conditions. Both the laser optical power and wavelength were continuously recorded during these cycles.

In addition, the laser has been subjected to gamma and protons irradiation. Three successive exposures of 1-MeV γ-radiation were applied to the laser prototype using a $^{60}Co$ source at increasing dose rates of 5 Gy/h, 10 Gy/h and 20 Gy/h, leading to a cumulated total irradiation dose (TID) of 200 Gy. Proton irradiation of the ECDL was performed using a cyclotron protons source at the University of Birmingham. Three different irradiations with a particles energy of 35 MeV, 30 MeV and 20 MeV, respectively, were used to cover both the effects of lower (20 MeV) and higher (35 MeV) particles. The γ- and protons-irradiation conditions were designed to achieve a total irradiation corresponding to the cumulated dose simulated for a 2-year mission on the outer platform of the ISS. The laser output power was measured as a function of the injection current after each irradiation step. No significant change of the laser performance was observed, neither on the threshold current (less than 1% variation was observed between the different measurements), nor on the slope efficiency. These tests constitute a first step towards the use of this laser technology in a future space optical clock.

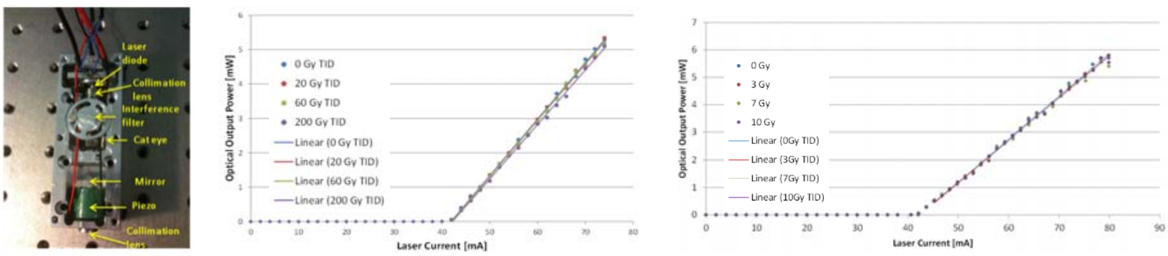


Fig. 1: Picture of the developed compact ECDL at 689 nm without its upper cover (left). L-I curves of the ECDL measured after different doses of γ-radiation (middle) and protons radiation (right). In both cases, the total irradiation corresponds to the cumulated dose simulated for a 2-year mission on the ISS.

# Ultra low noise Er:fiber frequency comb comparison


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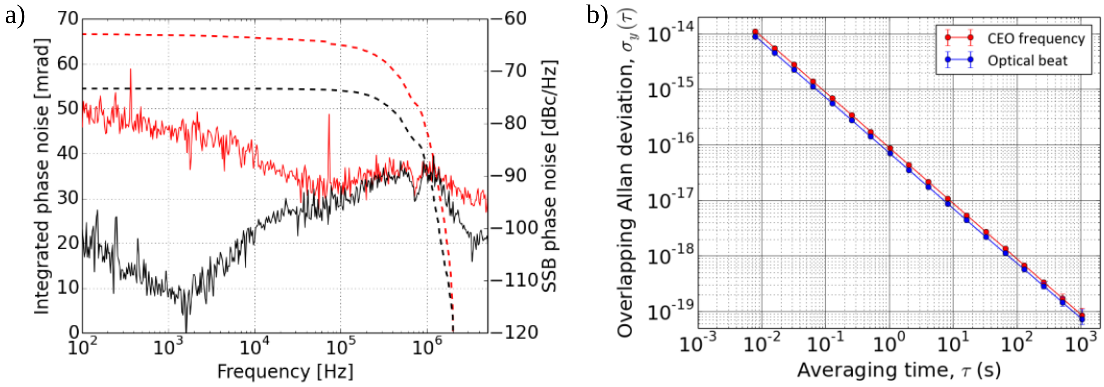
Ever increasing demand for stability and accuracy of time and frequency signals require improved oscillators and frequency references. Today's best clocks rely on narrowband optical transitions and use a frequency comb as clockwork. As their relative stabilities and accuracies both enter into the range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

Here we present an all polarization-maintaining (PM) and fully phase-locked Er:fiber frequency comb with ultra-high short-term stability. A nonlinear optical loop mirror (NOLM) is uased for mode locking and novel orthogonalized actuators allow for a control bandwidth larger than 1 MHz for both optical lock of 1 comb mode and offset frequency. An integrated phase noise below 70 mrad (100 Hz – 2 MHz) is reached for the full frequency comb. The locked beat signals exhibit an Allan deviation below $10^{-16}$ at 1s, averaging down below $10^{-19}$ at 1000 s. The modified Allan variance even reaches $3 \cdot 10^{-18}$ within 1s

For a full evaluation of both short and long term performance we have built and compared two such systems. Both systems are sitting on the same water cooled base plate and are locked to the same 1542nm optical reference laser (ADEV approx. 1 x $10^{-15}$ at 1 sec). The offset frequencies of the two combs are locked to 35 and 45 MHz respectively and the two combs are compared via a direct beat signal at a wavelength of 1064nm. The 10 MHz beat signal is evaluated by phase noise measurements and counter based measurements with Lambda and Pi type dead time free counters. In the direct comparison the phase noise of the out of loop comb – comb beat is below 100 mrad (100 Hz – 2 MHz). We reach an ADEV of 1 x $10^{-16}$ at 1 sec, dropping already below $10^{-18}$ at 1000 sec and reaching the $10^{-20}$ range after 20000 sec. The comb-comb comparison is therefore slightly worse than the out of loop performance of the individual combs. We attribute this to the far less than perfect temperature stability in our lab and the additional not stabilized fiber connections between the combs and the reference needed for the comparison. The comparison nevertheless surpasses the performance of any other comb comparison and also by far surpasses current optical clock performance.




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

# Higher-order and non-linear effects on precision of clocks of neutral atoms in optical lattices

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The results of numerical evaluations presented in this paper determine fundamental restrictions to various strategies of reducing uncertainties on optical lattice clocks of the group-II atoms. Detailed considerations of the use of strictly forbidden transition ${}^3P_0 - {}^1S_0$ for the time and frequency standard indicate possible methods of eliminating or accounting for the multipolar and higher-order dipole shifts of the clock levels. In particular, the difference between spatial distributions of electric-dipole (E1) and multipolar (M1 and E2) atom-lattice interaction is presented explicitly for an attractive red-detuned lattice. The case of repulsive blue-detuned lattice for Sr atoms is also considered in the paper.

The calculated data demonstrates really existing possibilities to overcome possible restrictions imposed by different effects of interaction between trapped atoms and the field of a lattice standing wave on the way to extending precision of atomic standards beyond the 18th decimal place.

In our paper, we have presented theoretical considerations of the most important effects on atoms in a lattice, which could constrain precision of atomic clocks. Corresponding polarizabilities and hyperpolarizabilities evaluated in a single-electron model-potential approach for the group II atoms are presented. Some data for susceptibilities of Sr, Yb and Hg, were completed and improved in comparison with corresponding data of [1,2]. Applicability to divalent atoms and corresponding modifications of the model-potential parameters were confirmed by agreement of calculated magic wavelengths (MWL) with the most reliable data of the literature: the data of the latest experimental MWL measurements for Sr, Yb, Ca and Hg. Dipole polarizabilities, hyperpolarizabilities and multipolar polarizabilities for neutral Ca, Sr, Yb, Zn, Cd and Hg atoms are calculated in the modified approach.

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# Theory of VCO Phase Noise Reduction Using Parallel Varactor Diodes

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Significant noise reduction has been observed by Rohde and Poddar [1,2] using several parallel varactor or capacitor switching diodes in a Voltage Controlled Oscillator (VCO) in place of single larger diodes. We theorize that the noise is correlated over the area of a single semiconductor diode by electromagnetic (EM) coupling, whereas the noise from discrete diodes is not correlated. For n equal discrete diodes the maximum reduction is n times.

For a silicon chip EM coupling can occur by surface waves on the chip or as bulk waves in the silicon substrate. In either case we find that the coupling factor between any parts of the chip is near unity and so any sources of noise are highly correlated whatever the area of the chip. On the other hand the EM coupling between discrete diodes can be essentially zero, unless they are brought very close together and left unscreened.

An interesting question remains. Using the Leeson oscillator model is the noise reduction associated with a commensurate reduction in the measured resistance of the paralleled diodes or is it a reduction of the noise temperature of the measured resistance of the combined diodes? More practical measurements are required to resolve this issue before the correct theory can be chosen and established.

From this theory it should be possible to postulate a multiple isolated section low-noise single chip varactor design with sufficient EM screening between the sections to de-correlate the noise between sections?

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# Optical to microwave synchronization with sub-femtosecond daily drift

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Narrowband voltage-controlled oscillators (VCOs) can be disciplined by an optical pulse train generated by a femtosecond mode-locked laser (MLL) to significantly improve its long-term stability. Such a perfect marriage requires a matchmaker who translates frequency and phase stability from optical domain to electronic domain. Here, we are using a hybrid balanced optical-microwave phase detector (BOMPD) to connect a 216 MHz MLL (OneFive) and a 10.8 GHz Sapphire-loaded cavity oscillator (PSI) together in the optoelectronic phase-locked loop (PLL). The measurement result (Fig. 1) shows long-term stable drift with sub-femtosecond RMS deviation for 24 hours of optical to microwave synchronization .

The BOMPD operation principle is based on balanced optical heterodyne detection with use of the fiber Sagnac interferometer [1]. In addition to the last modifications of the BOMPD scheme [2] with milti-GHz and, therefore, unidirectional phase modulation of the optical pulses in the Sagnac loop, we have implemented an independent RF demodulation arm for the error signal (Fig. 2). The signal demodulation is performed at the lowest possible frequency (half of the MLL repetition rate) to maximize SNR at photodetection and to minimize thermally- and humidity-induced phase drifts in the electronic and optical paths for long-term stability.

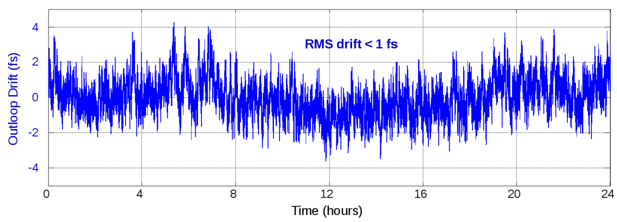


Fig. 1: Long-term timing drift for optical-to-microwave synchronization

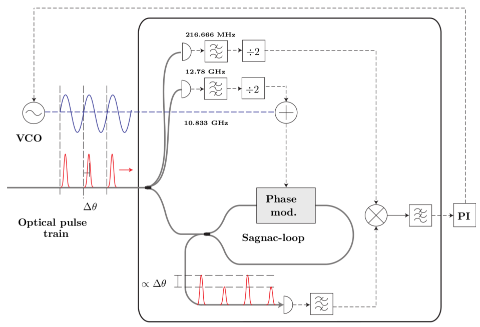


Fig. 2: Simplified schematic for a BOMPD-based optoelectronic PLL to synchronize a VCO to a MLL.

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# Frequency combs for astronomical precision spectroscopy

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

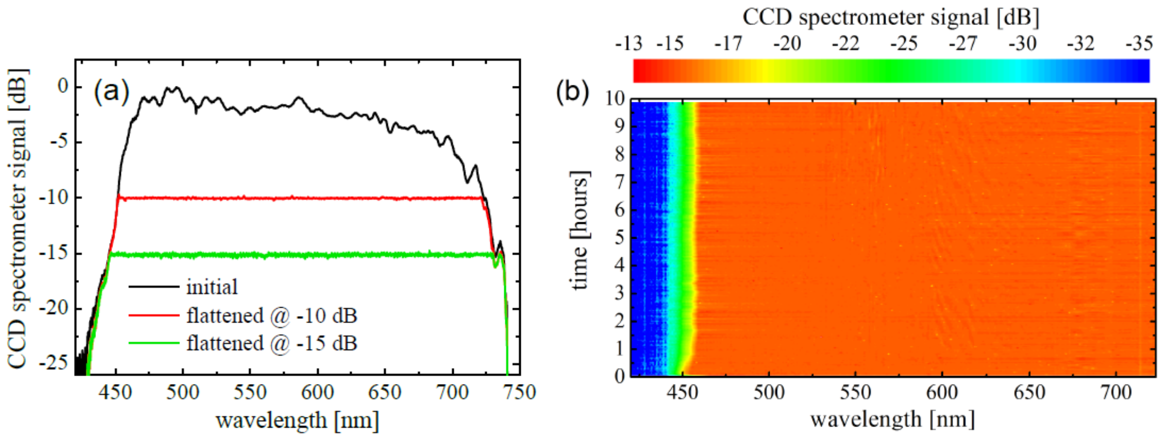


Fig. 1. LFC output spectra at a repetition rate of 25 GHz. (a) Spectra measured with the CCD spectrometer without spectral flattening (black line), and with active spectral flattening at different settings. (b) Temporal evolution of the spectrum over 10 h, with the flattening setup truncating the spectrum at -15 dB below its peak. The red area that fills most of the color plot is the flat-top region

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# Low Phase Noise 10GHz Bragg Resonator Oscillator

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This paper describes the theory and design of a 10GHz low noise oscillator which uses a Bragg resonator. The resonator utilizes an aperiodic arrangement of non ($\lambda_g/4$) low loss alumina plates ($\varepsilon_r$=9.75, loss tangent of ~1 to $2\times10^{-5}$) mounted in a cylindrical metal waveguide [1]. The resonator unloaded Q is around 200,000. The oscillator demonstrates a phase noise performance of –123 dBc/Hz at 1kHz offset and –153 dBc/Hz at 10kHz offset. To achieve these results extensive optimization of different transistors with different power level, gain and noise figure has taken place. Also, the residual phase noise of these amplifiers (measured using a broadband cross correlation system [2]) is reported. This enables a suitable choice for a given oscillator frequency. The power requirements of this oscillator are 6V at 52mA.

The oscillator is based on a feedback configuration consisting of a medium power amplifier, a 10dB output coupler, a tunable phase shifter and a Bragg resonator with wire loops being used to couple the energy in and out of the cavity. The unloaded Q of the resonator was measured to be 203,000. The insertion loss was set to be -6dB for optimum phase noise performance [3]. The amplifier used NBB-402 transistors from RFMD which demonstrated a gain of 10dB at 10GHz, a low power noise figure of 4.9dB (and a large signal noise figure of 8.1dB including phase shifter/cable losses) with an output $P_1$dBm compression point of 11.5dBm and a measured flicker noise corner around 26kHz.

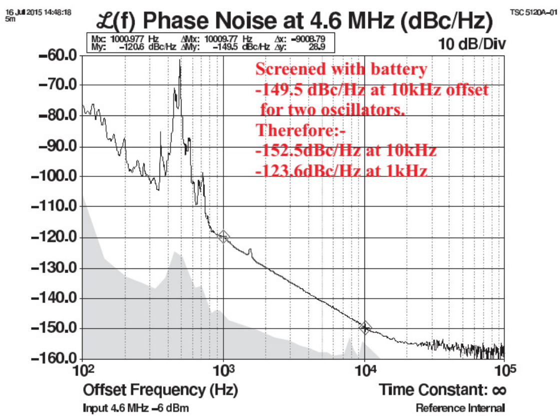


Fig. 1: Phase Noise of the 10GHz oscillator using NBB-402 transistors for an unloaded Q of 200,000 and a $P_1$dBm of 11.5dBm.

The phase noise of these oscillators was measured using the beat frequency of two very similar oscillators. Oscillator 1 had a frequency of 9.95GHz and Oscillator 2 had a frequency of 9.945GHz. These were downconverted using a mixer (MZ410CR) to produce a beat frequency of 4.6MHz. The LO drive level for the mixer was +10dBm. The phase noise was measured using a Symmetricom 5120A opt 01 which is an all digital phase noise analyser now made by Microsemi. The phase noise measurements are shown in Figure 1. The actual phase noise is 3dB lower assuming both oscillators are identical. The measured phase noise of these oscillators is within 1 to 2dB of the theoretical predictions.

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# National time scale and primary frequency standard of VNIIFTRI: current status

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The national time scale of the Russian Federation is reproduced and maintained based on the State standard of time and frequency operated at a facility located in Mendeleevo, Moscow Region. The aim of the VNIIFTRI system of primary frequency standards, comprising two caesium fountains, is to perform regular calibrations of the international time-scale TAI/UTC at the highest accuracy and to provide a stable reference for the construction and steering of UTC(SU), the local representation of UTC in Russia. The system of primary frequency standards can also be used for absolute frequency measurements of optical frequency standards using femto-second Comb techniques at VNIIFTRI. With both fountain standards fully operational, direct local comparisons on the level ~$10^{-16}$ in fractional frequency accuracy will be possible. Since 2014 caesium fountain CSFO2 is officially included in calculations TAI.

The national atomic time scale TA(SU) is computed in accordance with the definition of the SI second and the values of the units of time and frequency realized by primary cesium standards of the CSFO fountain, with an error of 5×10-16 or below.

The UTC(SU) time scale is currently transmitted to the GLONASS Ground Control Segment using signal receivers. According to the BIPM Circular T, the UTC(SU) time offset from UTC has not exceeded 10 ns in the current year (see, for example, Fig.1)

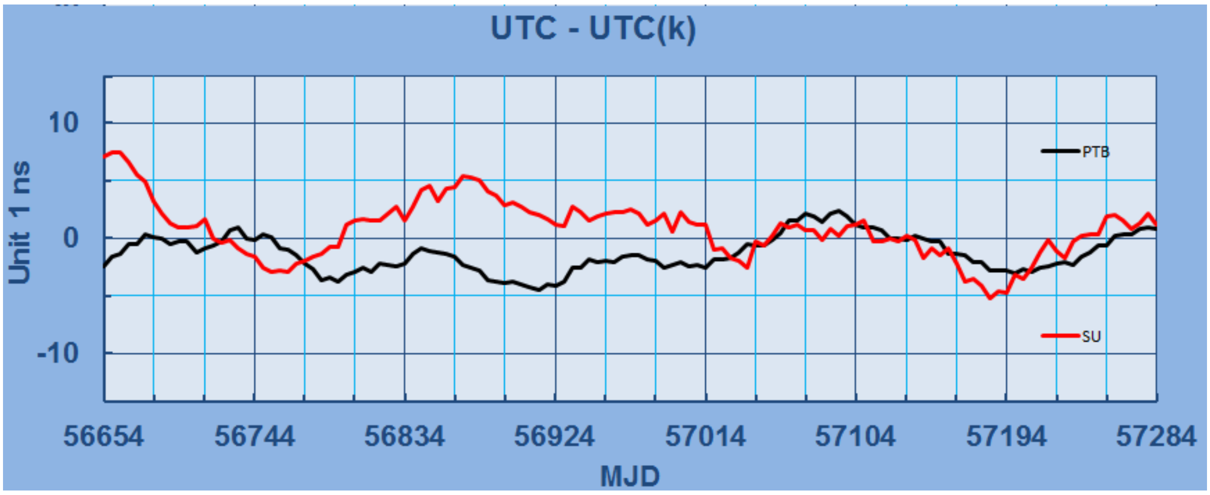


Figure 1. National local representations of UTC in Russia and Germany.

The UTC(SU) time scale is a representation of UTC; it is maintained in accordance with the BIPM requirements, based on the results of comparisons by GPS with the time scales of PTB, USNO, NIST with other time laboratories, and with time scales of Eu-Asian TWSTFT workgroup, including laboratories of Germany, China, Korea, India, Japan and Taiwan.

# Development of a strontium optical lattice clock for the SOC mission on the ISS

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Within an European Space Agency (ESA) program, the "Space Optical Clocks" (SOC) project aims to install and to operate an optical lattice clock on the International Space Station (ISS) towards the end of this decade. It would be a natural follow-on to the ACES mission, improving its performance by at least one order of magnitude. The payload is planned to include a strontium optical lattice clock, as well as a frequency comb, a microwave link, and an optical link for comparisons of the ISS clock with ground clocks located in several countries and continents. Within the EU-FP7-SPACE-2010-1 project No. 263500, we have developed a novel Sr lattice clock apparatus of modular design and consisting of compact subunits [1-3]. The goal performance is a fractional frequency instability below $1\times10^{-15}\tau^{-1/2}$ and a fractional inaccuracy below $5\times10^{-17}$. At present, the apparatus can reliably trap atoms in a vertical optical lattice and the first preliminary results for the spectroscopy on the clock transition have been achieved. The apparatus has been successfully transferred from Birmingham to PTB. As part of the aparatus, a compact ultrastable cavity setup has been developed with consideration of robustness against mechanical disturbances and against uncontrolled temperature changes. The 10-cm-long reference cavity is made of a ULE glass spacer and uses optically contacted fused silica mirror substrates in order to reduce the thermal noise floor. The cavity achieves $1.6\ \times10^{-15}$ fractional instability and has been successfully transported to PTB. We will present the most recent results of the Sr optical clock in SOC2 and also the novel compact design features, new methods employed and outlook. The research leading to these results has received initial funding by ESA, DLR and other national sources. Current funding has been provided by the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 263500. The work at PTB was also funded by the European Metrology Research Programme (EMRP) under IND14. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union. J. H. and D. S. acknowledge the funding from the EPSRC (EP/L001713/1) and Qtea (FP7-People-2012-ITN-Marie-Curie Action "Initial Training Network (ITN)"), respectively. S. O. was funded by the Marie-Curie Action ITN "FACT". S. V. acknowledges funding from the DFG within the RTG 1729.

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# On Efficiency of Laser Pumping for Selective Hyperfine-Level Population in Cesium and Rubidium atoms

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The optical pumping of the ground state hyperfine magnetic sublevels of $^{87}$Rb and $^{133}$Cs atoms is studied theoretically. Explicit expressions for the stationary populations of the "clock" sublevels during $F_g \leftrightarrow F_e{=}F_g$ and $F_f \leftrightarrow F_e{=}F_f$ transitions of corresponding $D_2$ lines in linearly polarized laser fields are obtained versus the initial values [1].

We show that almost all atoms are pumped to the lower "clock" sublevel $F_gM{=}0$ by changing the polarization direction in the $F_f \leftrightarrow F_e{=}F_f$ transition, which increases the signal intensity in the recording system of the rubidium and cesium frequency standards.

For example, the following three step sequence of pumping transitions with $\pi$- and $\sigma$- polarization:

$$F_g \leftrightarrow F_e{=}F_g\,(\pi) + F_f \leftrightarrow F_e{=}F_f\,(\pi) \to F_f \leftrightarrow F_e{=}F_f\,(\sigma) \to F_g \leftrightarrow F_e{=}F_g\,(\pi) + F_f \leftrightarrow F_e{=}F_f\,(\pi)$$

gives the final level populations

$$\bar{n}_{F_g=1,M=0} \approx 0.964, \quad \bar{n}_{F_f=2,M=0} \approx 0.036$$

for $^{87}$Rb atoms, and

$$\bar{n}_{F_g=3,M=0} \approx 0.934, \quad \bar{n}_{F_f=4,M=0} \approx 0.066$$

for $^{133}$Cs atoms with initially equilibrium populations.

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# Local Clocks Quality Evaluation Subsystem

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Modern research laboratories are more and more often equipped with several high quality clock sources, also atomic clocks. To perform reliable research based on the sources it is crucial to monitor their quality permanently. We propose a novel Clocks Evaluation Subsystem (CES), for continuous verification of parameters of local clocks. The main aim of the CES is to gather information about time drift of the clocks, then to evaluate their stability, and finally to select the most stable one as a local reference clock. The CES contains three main functional blocks (fig. 1): (1) three-channel precise Time Interval Counter (TIC), (2) Signal Distributor (SD) and (3) set of local Clock Sources (CS). The TIC allows for simultaneous measurement of time relations between pulses 1PPS generated by up to three clocks being under test and a single common 1PPS pulse from a reference, more stable clock (alternatively from GNSS). The counter provides a high measurement precision (< 15 ps) and wide range (> 1s) obtained by combining period counting with advanced two-stage time interpolation. The TIC is implemented in an ordinary programmable FPGA device Spartan-6 manufactured by *Xilinx*[1].

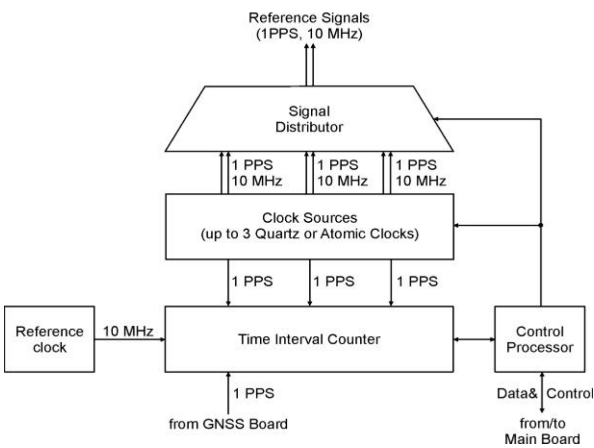


Fig. 1: Simplified block diagram of the CES.

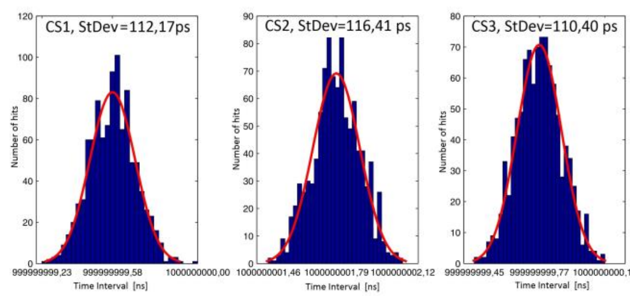


Fig. 2: Precision of measurements of 1PPS pulses from three tested rubidium chip scale atomic clocks (LN CSAC, *Microsemi*).

Functions of the SD are performed by digital switch implemented in FPGA device (with reference to 1PPSs) and by programmable analog high-speed crosspoint switch matrices (with reference to 10 MHz sine wave). Three low noise chip scale atomic clocks (LN CSAC, *Microsemi*) were applied as clock sources and integrated with the whole system on a single PCB board. In this paper we present the design and operation of the CES, as well as test results that include, among others, the TIC precision evaluation (fig. 2) and clocks drift.

This work was supported by the Polish National Centre for Research and Development under contract no. E! 8727LTDS/1/2014

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# Low Phase Noise 10MHz Crystal Oscillators

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**Summary:** This paper describes the design and implementation of low phase noise 10MHz Crystal Oscillators which are being used as part of the chain of a local oscillator for use in compact atomic clocks. The design considerations and phase noise measurements are presented. This paper is based on a previous design [1] but now demonstrates significantly improved phase noise performance and now includes the key circuit descriptions. The results compare well with the best 5MHz BVA oscillators when the 6dB (÷2) is incorporated.

**Introduction:** Short and medium term phase noise and Allan deviation of the local oscillator set the performance limits of most systems including vapour cell atomic clocks. Extremely low phase noise can be achieved by combining the close to carrier performance of crystal oscillators with the medium offset and the low noise floor of a DRO [2] and the narrow band digitally controlled tuning of a Direct Digital Synthesizer [3]. The resulting system is highly versatile in terms of tuning and locking the frequency to the atomic resonance and in terms of providing multiple highly stable output signals at RF and Microwave frequencies.

**Design:** The design of the crystal oscillators (the main concentration of this paper) is based on a feedback configuration which incorporates an amplifier, an electronic phase shifter for narrowband frequency tuning and a spurious oscillation rejection filter. The broadband amplifier includes a transformer coupled differential amplifier which simultaneously offers non-saturated limiting, noise matching, low flicker noise performance and crystal power control. The electronically tuned phase shifter is based on a 5th order high pass Butterworth filter incorporating varactor diodes and the spurious resonance rejection filter has a similar circuit to the model of the crystal resonator. The oscillator's output signal can be obtained directly from one of the amplifier's outputs without the use of an output coupler.

**Initial Results:** The latest measurements of the 10MHz crystal oscillator's performance show −123dBc/Hz phase noise at 1 Hz and −148dBc/Hz at 10 Hz. Further improvement in longer term stability is expected through improved temperature stabilization at the turnover temperature of the resonator. These results demonstrate close correlation with the theory [1] [4] and compare well with the phase noise of the best 5MHz BVA oscillators when 6dB (÷2) is subtracted.

**Acknowledgements:** The authors would like to thank SELEX-ES Ltd. and the UK Engineering and Physical Sciences Research Council (EPSRC) for providing a PhD studentship for Tsvetan Burtichelov.

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# Brillouin scattering in a lithium fluoride crystalline resonator for microwave generation

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We report Brillouin lasing in a monofluoride crystalline resonator for the very first time. While Raman scattering results from the interaction between a laser beam and an optical phonon providing a frequency shift in the THz range, Brillouin scattering results from the interaction between a strong laser beam and an acoustic phonon leading to a frequency shift of few GHz, which makes it more suitable for microwave generation. We present a time domain model which tracks the dynamics of the Stokes and pump waves and finally, with the help of a stability analysis, we determine analytically the threshold power. Such a laser has great potential for ultra-pure microwave and multi-wavelength generation.

Brillouin scattering was already evidenced in several difluorides crystalline resonators such as calcium fluoride [1]. Due to electrostriction, a refractive index grating created in the crystal can scatter the incident wave into the backward direction with a Doppler downshift. In our case, we report for the first time, to the best of our knowledge, Brillouin lasing at the wavelength of 1550 nm using mono-fluoride and specially lithium fluoride (LiF) crystal with the highest quality factor achieved so far: Q = $10^8$. As shown in Fig. 1, the Brillouin shift is $\nu_b = 13.61$ GHz, the acoustic wave speed $V_a = 7.62$ km/s. By analyzing the, temporal dynamics of the forward F(t) and backward fields B(t) using Equations (1) and (2), we found the threshold power to be $P_{th} = \omega_l{}^2 \frac{Q_{ext}}{Q_{tot}{}^2} \frac{A_{eff} T_r}{4 g_b v_b}$ with $\omega_l$ being the resonant wavelength, $Q_{ext}$ the extrinsic quality factor, $Q_{int}$ the intrinsic quality factor, $A_{eff}$ the effective cross-sectional area of the pumped eigenmode of the resonator, $T_r$ the cavity round trip, $V_b$ the group velocity dispersion. The equations are:

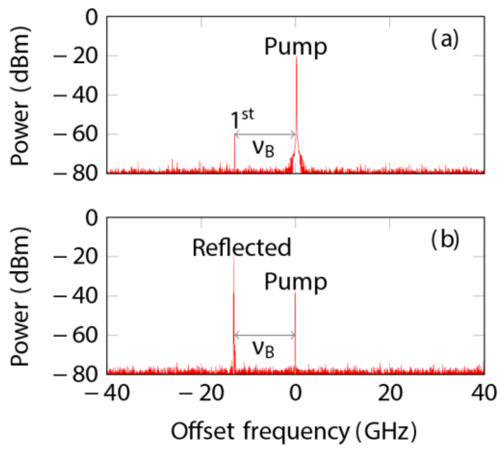


Fig. 1: Experimental spectra of the intra-cavity fields. The frequency corresponds to the Brillouin frequency shifts. (a) Forward direction. (b) Backward direction.

$$\frac{dF}{dt} = -\frac{1}{2}\Delta\omega_{tot}\mathrm{F} + i\sigma_f F - \frac{g_b V_g}{2A_{eff}} F - \frac{g_b V_g}{2A_{eff}} |B|^2 F + \sqrt{\frac{\Delta\omega_{ext}}{T_r}}\sqrt{P}$$

$$\frac{dB}{dt} = -\frac{1}{2}\Delta\omega_{tot}\mathrm{B} + i\sigma_b B - \frac{g_b V_g}{2A_{eff}} B - \frac{g_b V_g}{2A_{eff}} |F|^2$$

Where $P$ is the input power, and $\Delta\omega_{tot}$ is the loaded linewidth. We expect this analysis to enable a better understanding of phonon-photon interactions in bulk media, and allow for many applications in microwave photonics.

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

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

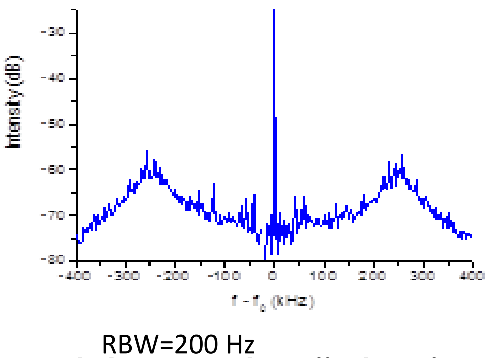


Fig. 1: Locked carrier-envelope offset beat of 1GHz Ti:Sapphire laser using direct pump current modulation.

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

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

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# Precision Measurements and Navigation with Frequency Measurements at the pHz Level

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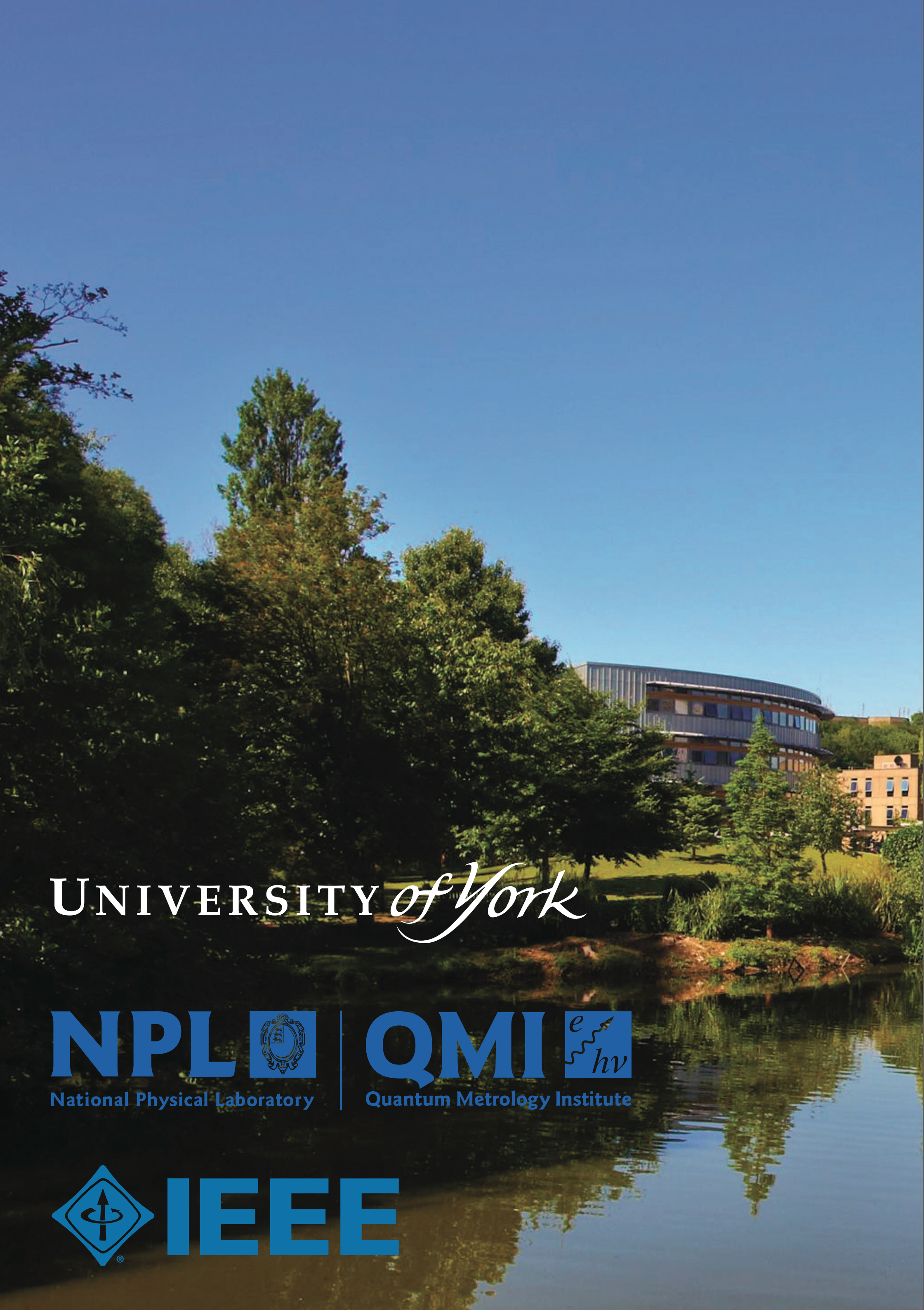
In this talk I will describe recent progress in using polarized nuclear spins for precision tests of fundamental physics as well as for practical applications, such as inertial rotation sensing. Nuclear spin polarized gases have particularly long spin coherence times, allowing for frequency measurements with precision down to the pHz level. This precision allows measurements of minute energy shifts that could be caused by new physics beyond the Standard Model. Such experiments can search for violation of fundamental symmetries, for example CP, CPT and Lorentz symmetries, and for long-range forces mediated by new particles, for example, an axion.

In our lab we have developed a co-magnetometer using a combination of an alkali-metal and a noble gas atoms, for example Rb and $^{21}$Ne. It can automatically compensate for drifts in the magnetic fields, allowing one to focus on non-magnetic spin interactions. The largest effect we observe is due to rotation of the apparatus. This points to a promising application as a gyroscope, but also introduces a large background for fundamental physics measurements due to Earth's rotation. To reduce this problem, we recently operated the co-magnetometer at the Amundsen–Scott South Pole station, where the quantization axis can be aligned with the Earth's rotation axis and the gravity axis, eliminating most sources of bias. This allowed us to improve limits on deviations from Lorentz invariance as well as on several types of spin-dependent forces.

We are also developing a new type of a co-magnetometer utilizing precession of two nuclear spin species, for example $^{3}$He and $^{129}$Xe. Here we focus on the accuracy of the precession measurements and eliminating experimental sources of bias. The nuclear spin precession is probed by optically pumped Rb atoms, but the measurements rely on long spin precession in the dark, when Rb spins are actively depolarized by RF fields to eliminate small frequency shifts due to spin-exchange collisions. This arrangement is particularly promising for inertial rotation sensing as well as to search for new forces that cannot be easily modulated, for example spin-gravity interactions.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