TC Chair Annual Report 2015 - 2016

TC for Time and Frequency (TF)
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1. General Aspects – Heading Arial 12 bold

Currently 30 countries are represented in the EURAMET Technical Committee for Time and Frequency and the list of contact persons is published on the EURAMET web site. These institutes contributed for the generation of the UTC time scale using more than 130 commercial Cs and H masers. The different CNSS receivers used during time scale generation and the results related to national time scales and uncertainties are published on BIPM web site. Several institutes used primary frequency standards which are used also for time scale generation. Traceable time and frequency information is disseminated using different methods. A list of time dissemination services is available on the BIPM web site. The main aims of research and development projects and comparisons are the development of new standards for time scale generation and industrial applications, dissemination of time and frequency information with low uncertainty, and the comparison of reference equipment for improvement of type B uncertainty in time scale generation. Information about ongoing projects and EMRP projects is given below. Especially for last 1 year EURAMET TCTF community mostly concentrated to the GNSS comparisons as G1 and G2 laboratories, time interval comparisons at few ps level using travel standards and high frequency oscilloscopes. Two important EMPIR projects were prepared related development Optical Clocks with 10^{-18} uncertainty and improvement of optical frequency comparisons up to 10^{-19} level.

2. Projects

List of current EURAMET project on TCTF is given below:

Project 1303, On-site visits by external technical experts in the fields of electricity and magnetism, thermometry, time and frequency and length (Coordinator: FTMC)
Project 1288, Time interval comparison Pilot Study, (Coordinator: MIRS)
Project 1156, GPS link calibrations in support of CCTF-K001.UTC, (Coordinator: ROA)
Project 1152, GNSS receiver performance monitoring,(Coordinator: GUM)
Project 1146, Time Transfer using optical fiber links, (Coordinator: UFE/IPE)
Project 1130, Preparation of a EURAMET guideline for the assessment of calibration laboratories using GPS signals for frequency and time traceability, (Coordinator: NPL)

The work for the following projects is ongoing:

Project 1303, proposed by FTMC. This project is a consultancy project and will be realized by the external technical experts in the fields of electricity and magnetism, thermometry, time and frequency and length. NMIs and DIs participating CIPM MRA have to operate a QMS in conformity with ISO/IEC 17025 to support their measurement and calibration activities. This project of QMS peer visits and reviews is intended to support evaluation of QMSs in VMT/FTMC, VMT/VMC and GUM, the development and improvement processes and provides a tool for a better international recognition and fulfillment of the requirements of CIPM MRA. The goal of the project is to review the measurement capabilities of the laboratories in VMT/FTMC, VMT/VMC and GUM, including the declared measurement uncertainty in some specific fields of metrology; detect, analyze and resolve possible metrological problems of the laboratories and also learning from each other and sharing the best practice for QMS implementation. Last year under this project realized good progress with an on-site visit by technical experts from Poland. This project should finish this year.

Project 1288, coordinated by MIRS is second stage of the EURAMET project 828. In the proposed Pilot Study project 1288, different travelling standards for time interval comparison are studied and prepared and cable box as provided from BEV will be investigated again. Necessary measurements on these travelling standards will be performed by Pilot Study participants (AGH and NIT (Poland), SIQ (Slowenia) UME (Turkey), SASO (SA). The Inter-Laboratory Comparison (ILC) Protocol (and especially measurement parameters and methods) will be correctly defined so as to enable to launch a EURAMET TF.TI-K2 to serve as a EURAMET Supplementary comparison.
The project activities are:
- Study and build of new transfer standards
- Study on using existing cable box
- Performing verification measurements
- Preparation of detailed and harmonised ILC Protocol.

In the TC-TF 2016 Meeting, MIRS give a short report on recent developments. The Slovenian company InLambda has produced a prototype of the fibre-based time interval standard, and the 50 ns and 200 ns versions will be ready soon. The GUM electronic delay standard has been sent to several labs for testing and characterization for stability, repeatability and temperature dependence, and is performing well. The InLambda standard is internally stabilized to maintain the fibre at about 35 C, but control fails when the external temperature rises to 27 C.

GUM test results for the InLambda standard, which displays some dependence on frequency as well as on pulse level and pulse width, but is stable enough to be a travelling standard provided that the conditions of measurement are defined very carefully. Finally the tested travel standard generates 127 different Time Intervals between 1 pps outputs (from 20 ns to 12 µs). Result of investigation show that expanded uncertainty of the travelling standard is about 3 ps. In the comparison which completed in this year by pilot study participant used two type of measurement equipment: high frequency oscilloscope and time interval counter. Comparison results show that, measurements with oscilloscope agree within a few ps, but measurement with time interval counter is very surprising and agrees within more than 100 ps.

Project 1156, led by ROA (ES) on performing regional campaigns of GPS (in the future GNSS) receiver characterization, in reaction to Recommendation 2 of CCTF 2009. To the calibration of receivers ROA, PTB, INRIM, OP and NPL were involved. Project, which started in May 2010 and now has 17 participating partners.

Currently in EURAMET TCTF as G1 laboratories are PTB, OP, ROA. G1 and G2 laboratory comparison organized by PTB as G1 are include following G2 laboratories: VSL, METAS, DLR and BEV. G1 and G2 laboratory comparison organized by ROA as G1 are include following G2 laboratories: UME, BIM, BOM, IMBH, INRIM. A G2 calibration campaign has recently started, concentrating on labs in south-east Europe. ROA travelling equipment currently used in comparison by G2 laboratories. A second campaign organized by PTB will start in April 2016.

Project 1152, led by GUM (PL) on studies of GPS receiver performance in dependence on environmental parameters. Results from GPS receiver comparisons studied in the project (currently receivers in BEV, UFE, GUM, SP, PTB) have been presented. In the TCTF-2016 GUM reported on progress on the project, which is now into its 5th year. A range of anomalies have been observed. Time steps visible in data from the TTS-2 receiver were traced to the DC power supply, and cured by replacing the processor. Large temperature variations observed in the TTS-2 – GTR50 time difference variation (20 ns).

Project 1146, led by IPE (CZ) on time transfer using optical fibers.
This project was initially launched as a bilateral project. The work done in this project is one part of the activities continued now in the frame of NEAT-FT. In the TC-TF 2016 meeting, IPE gave an update on recent activities. The Prague to Vienna link of around 560 km, using a single channel of a telecom fibre pair, achieves a TDEV of around 30 ps. The link between UFE, CESNET and the Geodetical Observatory Pecny uses around 100 km of single fibre with a channel in each direction.

Project 1130, led by NPL (UK) on GPS disciplined oscillators. The objective is to produce a EURAMET Calibration Guide on the use of GPS disciplined oscillators as reference standards for frequency or time in calibration laboratories. Document preparation started as a EURAMET project in 2009. The guide was revised based on discussions during and after the 2015 TC-TF meeting, and it was submitted to the EURAMET Secretariat in late 2015 for approval. A few last-minute changes proposed by PTB have been made to the document, in particular the addition of averaging times to several instability values, and on 26 February the EURAMET Board of Directors approved its publication as Technical Guide no. 3. Currently Technical Guide is published and available on the EURAMET website.

3. Comparisons

Last 1 year two main comparisons were done in EURAMET TCTF.

First of them is pilot study time interval comparison (75 ns, 1.1 μs, 4.7 μs, 10.6 μs) under Project 1288. AGH and NIT from Poland, SIQ from Slovenia UME Turkey and also SASO from Saudi Arabia attend to this comparison using travelling standard expanded uncertainty about 3 ps. In the comparison which completed in this year by pilot study participant used two type of measurement equipment: high frequency oscilloscope and time interval counter. Comparison results show that, measurements with oscilloscope agree within a few ps, but measurement with time interval counter is very surprising and agrees within more than 100 ps. It is necessary to note that this pilot study comparison demonstrate that travel standard is ready for Supplementary Comparison.

Second of them is GNSS comparison under Project 1156, GPS link calibrations in support of CCTF-K001.UTC for improvement of type B uncertainty with targeting value 2-3 ns in time scale generation. For many years the BIPM Time Department had organised international calibration campaigns for the GPS and more recently GLONASS receivers used by many laboratories for the inter-comparisons of their atomic clocks, which allow them to participate in the only time and frequency key comparison, CCTF-K001.UTC. Recently the BIPM Time Department prepared “BIPM guidelines for GNSS equipment calibration” master document. This master document is discussed on TC-TF 2014 and new activity related comparison of GNSS receivers started in this year. This work is very important for improvement of type B uncertainty with targeting value 2-3 ns in time scale generation which is given in the Circular T published by the BIPM.

In EURAMET TCTF as main pilot G1 laboratories for GNSS comparison are decide PTB, OP, ROA. G1 and G2 laboratory comparison organized by PTB as G1 are include following G2 laboratories: VSL, METAS, DLR and BEV. G1 and G2 laboratory comparison organized by ROA as G1 are include following G2 laboratories: UME, BIM, BOM, IMBH, INRIM. A G2 calibration campaign has recently started, concentrating on labs in south-east Europe. ROA travelling

equipment currently used in comparison by G2 laboratories. A second campaign organized by PTB will start in April 2016.

4. CMCs

Within the TC, there are 4 delegates who carry out CMC reviews (Andreas Bauch, Peter Whibberley, Anton Niessner, Kenneth Jaldehag), and this year there has been review of CMCs submitted by INTI (SIM.TF.12.2014) of Argentina, TL (APMP.TF.13.2014) of Taiwan, SNM - INDECOPI (SIM.TF.9.2014) of Peru, ICE (SIM.TF.11.2014) of Costa Rica, INM (SIM.TF.10.2014) of Colombia, COOMET.TF.7.2014 of Kazakhstan. In general, the process of the inter-RMO review of CMCs was noted as smooth and cooperative. The support of the JCRB Secretariat at BIPM is greatly appreciated. This year Institute of Metrology of Bosnia and Herzegovina prepared CMC table and related document for the stopwatches (timers) calibration, general frequency source: direct measurement (calibration) of frequency, period, time interval and pulse width, characterization of state standard for time and frequency, time scale difference, pulse rise time measurement (calibration) using oscilloscope. This CMC table, and related document now under evaluation of NPL.

5. Activities of the Subcommittees

TC-TF has no sub-committees.

6. Participation in EMRP/ EMPIR

List of EMRP projects in TC-TF is given below:

- SIB04, High-accuracy optical clocks with trapped ions
- SIB55, International timescales with optical clocks
- EMPIR OC18: Optical clocks with 1E-18 uncertainty
- SIB02, Accurate time/frequency comparison and dissemination through optical telecommunication networks
- Optical frequency transfer- a European network
- IND55, Compact microwave clocks for industrial applications
- SIB60, Metrology for long distance surveying
- EXL01, Quantum engineered states for optical clocks and atomic sensors

Project results presented at the 2016 TC-TF meeting.

Short new information about EMRP projects are given below:

SIB04, Ion Clock - High-accuracy optical clocks with trapped ions, Coordinator Ekkehard Peik (PTB)

This JRP addresses the development of ultra - precise optical clocks using laser - cooled trapped ions. The combination of laser cooling and ion trapping provides an ideal spectroscopic system

that permits the observation of unperturbed atomic frequencies, thus laying the foundation for atomic clocks of the highest accuracy. The realization of the unit of time plays a central role within the SI because of its unequalled precision and because it is also used in the realizations of other units, such as the meter, volt and ampere.

In WP1, PTB and NPL have constructed new micro trap designs and demonstrated their operation. CMI have developed an improved resonator design in WP2, and MIKES is working on an improved vacuum enclosure for its resonator, currently being vacuum baked before evaluation. MIKES have also developed DFB laser sources for its Sr+ ion trap. Under WP3, CMI have developed a finite element model for ion trap heating that has already been used by PTB, and the dominant shifts have been evaluated. WP4 includes new Cs-referenced measurements of the Yb+ and Sr+ quadrupole and the Yb+ octupole transitions from both PTB and NPL.

Project successfully finished in 2015. Under WP1 improved endcap traps have been developed by PTB and NPL, and a trap is being constructed by MIKES to a slightly modified NPL design. Heating rate issues have been addressed, and a linear trap developed. WP2 covers improvements to the lasers, including thermal noise and vibrations in the reference cavities. VTT has worked on fibre-based light sources that are much more transportable. Frequency shifts were investigated in WP3, PTB have made a precise measurement of the static polarizability of Yb+, and the thermal radiation emitted by trap structures has been both modeled and measured, pointing to a shift in the low 10-18 range for several ions. The hyper-Ramsey method to remove the light shift in Yb+ has also been studied. WP4 covered absolute frequency measurements of Sr+ and Yb+ at NPL, and satellite comparisons of the NPL and PTB Yb+ clocks. The project has considerably advanced optical clock development at VTT and CMI.

SIB55, ITOC - International timescales with optical clocks, Coordinator Helen Margolis (NPL)

- Partners: CMI (CZ), PTB (DE), MIKES (FI), LNE (FR), OBSPARIS (FR), INRiM (IT), LUH(DE), CNRS (FR), UPMC (FR),
- Duration 3 years, started 2013,
- Aim: Tackle key challenges before any future optical redefinition of the second,
- Sectors: International metrology community,
- Output: The possibility of a future redefinition of the second in terms of an optical transition frequency.

WP1: Local frequency comparisons and absolute frequency measurements,
WP2: Frequency comparisons using transportable optical clocks,
WP3: Relativistic timescales and geodesy experiment,
WP4: Remote clock comparisons via satellite links and analysis for timescale.

Key Deliverable:

- Comparison at 10^{-17} - 10^{-16} level,
- Future optical redefinition of the second.

The JRP covers a range of activities in support of an optical redefinition of the SI second and the use of optical clocks in time scales. Progress has been made with all of the optical clocks supported by the project, though with slower progress than intended, and the PTB transportable Sr lattice has now been operated after transport for the first time. An important component of the project is a broadband TWSTFT campaign linking all four labs with suitable earth stations, which

was carried out over 25 days in June 2015. Six optical clocks ran during the campaign, and typically collected data for 60-80% of the period. Data analysis is continuing.

Least squares analysis software developed during the project has been used to compute optimal values for several optical clock frequency ratios that were submitted to, and accepted by, the CCTF WGFS in September 2015. Other work has addressed relativistic effects in TWSTFT, fibre links and continuously-operating portable clocks. The gravity measurements carried out by the REG team from the Liebnitz University of Hannover have contributed to an improved model of the European gravimetric geoid.

An important element of the project is a proof-of-principle demonstration of clock-based geodesy using the PTB transportable Sr clock and the INRIM Yb lattice at either end of a 90 km fibre link between LSM and INRIM, with an elevation difference between the clocks of 1000 m. This experiment started at the beginning of February 2015 and was continuing into March 2015. Impact activities have included a very successful summer school on optical clocks held in Turin in late June – early July 2015. On 8 April 2016 was a workshop at the University of York, UK for the dissemination the outcomes of ITOC project.

EMPIR OC18: Optical clocks with 1E-18 uncertainty

- JRP Coordinator: Rachel Godun, NPL

The project was approved within the EMPIR 'SI broader scope' call in 2015 and will run for 3 years from May 2016. Its aim is to push the instabilities and systematic uncertainties of optical clocks towards the 1E-18 level, and to verify the uncertainties through direct measurements. The consortium partners consist of 8 NMIs, universities in Hannover, Copenhagen and Torun, and CNRS in France.

Project includes 4 technical work packages. WP1 addresses improvements to laser stability and means to transfer that level of stability to the atoms, and WP2 will develop ion traps and lattices that can support longer (>1 s) probe times to give sub-Hz resolution. WP3 will target improvements in systematic uncertainties towards 1E-18, while WP4 studies methods of operating clocks that can take advantage of the improved uncertainties, as well as comparisons of co-located clocks. The parallel OFTEN project will address fibre-based frequency comparisons.

The project impact work package includes a summer school in Turin and a publication of a document that will provide specifications and guidance on construction and operation of optical clocks.

SIB02, Accurate time/frequency comparison and dissemination through optical telecommunication networks

- JRP Coordinator: Harald Schnatz, PTB

Project successfully finished in 2015. WP1 developed methods for frequency transfer at the 1E-18 level at 1 day, including amplifiers and multi-user distribution. WP2 demonstrated long-distance fibre link capabilities, including PTB-SYRTE and NPL-SYRTE, and the links in Italy. WP3 addressed novel T&F transfer methods, achieving very good results on dark fibre links in the UK. WP4 similarly looked at novel methods for long distance time transfer, using a range of methods tested in Sweden, the Czech Republic and Poland. The White Rabbit (WR) protocol was

investigated in the Netherlands (using 2 channels in 1 fibre) and Finland (2 fibres), including a comparison with GPS PPP.

Additionally to this successful SIB02 project there are 2 follow-up EMPIR projects: OFTEN on coherent optical frequency transfer and TIMEFUNC (coordinated by VSL) on the deployment of WR time transfer to users. SuperGPS project, a collaboration between VSL, VU Amsterdam and TU Delft which has been approved in an internal Netherlands research call. It will study time and positioning based on distribution over optical wireless signals. In additionally, DAB transmission network in Norway is already synchronized country-wide and could be used in a similar way.

Optical frequency transfer- a European network (OFTEN)

- JRP Coordinator: Harald Schnatz, PTB

EMPIR OFTEN project, due to start in 2016, on behalf of the coordinator Harald Schnatz (PTB). The project aims to move towards a European network of fibre links between NMIs for coherent optical frequency comparisons, and to improve the technical readiness closer towards routine automated operation. Applications such as ACES and relativistic geodesy will also be supported. WP1 focuses on optical clock comparisons with instabilities and uncertainties below 1E-17, including establishing, testing and operating links between NMIs with at least two 1-week campaigns. WP3 similarly covers Cs fountain comparisons, with the target of reliable, fast link operation. WP2 covers improvements to optical frequency transfer, in particular improved reliability and automation to allow continuous measurements over more than 1 day, and simultaneous dissemination to multiple users. WP4 aims to provide fibre link capabilities for non-NMI users, including ACES, relativistic geodesy and VLBI, and frequency links to other labs including INRIM-LENS (Florence), Medicina and Matera, SYRTE-LPL, and PTB-LUH. The WP will also address widespread frequency dissemination to users with better than GPS performance over distances up to 5000 km.

IND55, MCLOCKS - Compact microwave clocks for industrial applications

- JRP Coordinator: S. Micalizio, INRIM
- Partners: UME (TR), SYRTE (FR), UFC (FR), Université de Neuchatel (UniNe-LTF), Switzerland, CNRS (FR)
- This JRP is supported by the following stakeholders:
- Spectratime, DGA, CNR, Spectracom, Thales Electron Devices SAS,
- Thales R&T, CSEM, METAS, Selex Galileo, Italian Space Agency (ASI)
- Duration 3 years, started 2013
- Aim: Development reliable and hand-held standards for wide industrial applications
- Sectors: Telecommunication networks, satellite navigation, research
- Output: development of compact and high-performing microwave clocks based on the vapour-cell technology

Key Deliverable:

- Robust and compact, optimizing size, reliability and suitability to operate in industry
- To offer better accuracy
- Realization of hand-held clock with frequency stability in range 10^{-10} - 10^{-12} at 1 s

The aim of the project is to develop novel vapour cell-based microwave clocks of 3 types: two compact 'master clocks' with comparable performance to hydrogen masers, and a miniature clock with somewhat lower performance. One of the high performance clocks is the pulsed optically-pumped (POP) Rb, using thermal atoms in a cell. A novel magnetron cavity has been developed, along with a new low phase-noise synthesis chain. The second high performance clock is the Rubiclock, based on cooled atoms using isotropic light cooling. Preliminary results give 1E-15 stability at 10000 s, and the clock has been tested in zero-g parabolic flights. The compact clock is the CPT clock based on a Cs vapour cell. The project has already demonstrated considerable impact through publications and conference presentations. There are considerable potential uses for all of the clocks being developed as well as market opportunities for European companies, and technology transfer to industry is already in progress.

SIB60 Surveying: Metrology for long distance surveying,
Coordinator: Florian Pollinger (PTB).

The aim of this project is improvement and comparison of distance measurement by laser and GNSS receivers with mm uncertainty, traceable to definition of meter.

Project is important for improvement and understanding of the uncertainties in GNSS-based distance measurement between two receivers, looking at factors such as antenna phase centre offsets, multipath and local oscillator performance. A model developed by University of Hannover has been modified by PTB for this application. Under a REG, the University of Bonn has carried out a number of antenna calibrations and developed components for use in antenna testing. PTB measured phase plot for a Leica antenna, and demonstrate importance of the antenna phase centre (APC) coordinates in achieving the 3 cm accuracy (equivalent to 0.1 ns) proposed by the CTF WG CGGTTS in its new guidelines. Recent results from PTB have shown discrepancies between 2 antennas that have not yet been explained. Andreas also described the methods installed for frequency and time distribution between buildings at PTB, and noted a 0.8 ns discrepancy between a simple modulated time transfer method and time transfer using Satre modems at both ends.

EXL01, QESOCAS - Quantum engineered states for optical clocks and atomic sensors,
Coordinator Sebastian Bize (SYRTE).

The JRP addresses these key factors that hamper progress towards uncertainties at the 10^{-18} level. Such performance in hand would be beneficial to most major applications of clocks and open the possibility of new applications. To tackle these two noise sources, in the JRP the possibility offered by quantum mechanics to create and exploit entangled states shall be investigated, showing quantum correlations between multiple atoms or ions, and to detect these states in a non-destructive manner. These states are referred to as Quantum Engineered States. The project aim is to investigate how quantum engineered states (QES) can improve optical clocks and atomic sensors, reducing noise and improving accuracy and sensitivity. Under WP1, led by PTB, a range of methods are being studied to prepare QES by interactions in atoms and ions. OBSPARIS has demonstrated trapping of Sr atoms in WP2, while WP3, led by NPL, includes a range of studies of spectroscopy and clock operation using QES.

7. Capacity Building: Activities of the last year and future needs

SRT-r05 international traceability for time and frequency measurements PRT was offered by Institute of Metrology of Bosnia and Herzegovina (MET) and partnering meeting was done 29th – 30th June 2015 at BEV in Wien. UME, NSAI, DMDM and Norwegian Metrology Service was attended the meeting. Since its technical difficulties JRP was not offered. For improvement of joint work capability and calibration services TCTF will continue work and applications related capacity building.

8. Meetings

The 2016 TC-TF meeting was at the MIKES Metrology, VTT Technical Research Centre of Finland on 1th and 2th of March 2016. At this meeting, we discussed EURAMET projects, EMRP projects, CMCs and other new projects. The next annual meeting of the EURAMET Technical Committee for Time and Frequency plan in ROA.

9. Issues

Recently EURAMET signed an agreement with the European Space Agency (ESA) with the aim to improve the technical collaboration in fields of common interest. One of the identified technical fields is time and frequency. The ESA experts suggest the following areas of cooperation, where the respective expertises are complementary:

- Timescale generation and distribution (including algorithms)
- Time and frequency transfer and comparison (GNSS, Two-way and optical fibre)
- Time and frequency measurement, calibration and uncertainty estimation.

In additionally it is necessary to note that financial support for traditional EURAMET research projects/comparisons. Also TCTF need encouragement of joint collaboration and research involving small NMIs, effective using of Researcher Mobility Grants and joint work for improvement of calibration services.

10. Strategic Planning

During last one year under EIRAMET coordination prepared very important document „Strategic Research Agenda for Metrology in Europe“. This document also includes Time and Frequency Metrology strategy for next 10 year. Draft of this part prepared by TCTF chair based available documents, roadmaps. In short main strategy and targets are given below:

- The development of accurate ground atomic clocks

Target accuracy: from 10^{-14} - 10^{-15} to 10^{-17} - 10^{-18}

- Space applications of atomic clocks and time-frequency metrology

Target accuracy of clocks on space: $1x10^{-16}$ - $1x10^{-17}$ for next 10 years.

- Time and frequency dissemination and comparison

In ground $<10^{-18}$ and <0.1ns; In Space $<10^{-16}$ and <0.1ns

- Accurate time scale generation and traceability (from 7ns to <2 ns)

This strategy is important for redefinition of the second and for application in gravity wave detection, fundamental constant, gas detection, space, navigation and communication.

11. Outlook for 2016/2017

- Complete GNSS G1 – G2 Laboratory Comparisons. Participants of these important GNSS comparisons include PTB and ROA as G1 Laboratories and VSL, METAS, DLR, BEV, UME, BIM, BOM, IMBH, INRIM as G2 laboratories.
- Start activity on two EMPIR projects (Optical Clocks and OFTEN)
- Complete IND55, MCLOCKS - Compact microwave clocks for industrial applications

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