Report from NPL to the 21st session of the Consultative Committee for Time and Frequency (CCTF), 2017

Microwave frequency standards

NPL has developed and built a number of cold atom fountain clocks for its own use as primary frequency standards and to be installed in other NMI laboratories. Key features of the NPL design include: a simple cold atom source based on a single-stage vapour cell magneto-optical trap, optical pumping for accumulation of the atomic population in the clock sub-state (m_F=0), operation near a zero-collisional shift point, and a novel microwave cavity designed to minimise the distributed cavity phase effect. In addition, a new optical setup for the cooling, optical pumping and detection has recently been developed. The new setup has a modular design with a small footprint and allows stable and robust operation without unintentional interruption for several months.

Two fountain standards are now operational at NPL. NPL-CsF2 was first characterised in 2009 and then reassessed in 2011 and 2013 giving $u_B = 2 \times 10^{-16}$ [1]. After several years of operation this fountain required an upgrade, so an optical setup of the new design and a new electronic control system are currently being implemented. No changes to the physics package of NPL-CsF2 are envisaged at this stage. NPL-CsF3 was provisionally evaluated in 2015 [2] with full evaluation pending an optics upgrade similar to NPL-CsF2 and the full implementation of a new local oscillator. This oscillator uses an optical frequency comb to transfer the stability of an ultrastable laser to the microwave region. During the upgrade work, fountain data were used internally for monitoring and steering the time interval of the local timescale UTC(NPL).

In 2015 NPL entered into a collaboration with AOS Borowiec (Poland) and NRC Ottawa (Canada), which included contracts for delivery of two complete fountain systems to AOS and a physics package to NRC. One system for AOS and the fountain for NRC were delivered in 2016 after successful testing at NPL.

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UTC(NPL) time scale

NPL is the only institute in the UK that maintains a UTC(*k*) time scale and contributes to the generation of UTC [3]. We have participated in rapid UTC (UTCr) since February 2017. As of May 2017, the UTC(NPL) time scale was based on five active hydrogen masers and two high-stability commercial caesium clocks. The most recent addition, an iMaser 3000 manufactured by T4Science, was brought into operation in December 2015. The masers are distributed in three locations in different parts of the NPL building and the key time scale systems are duplicated. The resilience of the time scale has also been enhanced through a programme of investment in new and replacement equipment.

At present, UTC(NPL) is generated from a Datum (now Microsemi) model MHM-2010 maser that is adjusted in frequency usually 3 times each week, based on measurements of its frequency difference from one or more of the NPL caesium fountains, with additional monthly corrections to maintain alignment with UTC. Work is in progress to automate the procedure for daily frequency steering to fountain measurements. UTC(NPL) will then be based on a frequency offset generator (SpectraDynamics High Resolution Offset Generator) synchronised to the reference maser, and two other frequency offset generators linked to other masers will provide closely-aligned backup realisations of the time scale.

NPL operates both of the standard methods for performing regular time and frequency comparisons with other timing institutes. A two-way satellite time and frequency transfer (TWSTFT) earth station, designated NPL02, was brought back into operation in May 2016 following relocation from a different building and equipment failures. A second earth station is being assembled as a backup system. The hardware and software for the Software-Defined Radio (SDR) pilot study have been assembled, and work is in progress to bring the system into operation. The main GNSS timing receiver at NPL is a Mesit GTR51 dual frequency carrier-phase receiver, designated NPL2, and a Dicom (now Mesit) GTR50 GPS-only receiver designated NPL1 is in operation as backup. Both receivers were calibrated in a measurement campaign coordinated by ROA in May 2017.

A range of NPL services disseminate time and frequency. The MSF 60 kHz standard frequency and time signal, transmitted from Anthorn radio station in Cumbria, is the most widely used source of traceable time within the UK. For users requiring greater accuracy, NPL offers a GPS common-view service that offers direct and continuous traceability between a remote reference clock and UTC(NPL) with an uncertainty of better than 20 ns. This service provides formal frequency traceability to UTC for the Irish NMI, NSAI NML in Dublin. NPL also operates two services that disseminate time to computers: a dial-up service utilising the European telephone time code, and NTP-based internet time servers. Frequency standards and GPS-disciplined oscillators can be calibrated at either NPL or a customer's site. The calibration service and the GPS common-view service are accredited by the UK Accreditation Service (UKAS).

A new service known as NPL*Time*® has been developed for time distribution over optical fibres to the financial sector and other organisations around London. The service is resilient and traceable to UTC, and is monitored, managed and certified by NPL to ensure that it is fully compliant with the MiFID II regulations from the European Securities and Markets Authority (ESMA), which come into effect in January 2018. It uses commercially-available equipment employing the precision time protocol (PTP, or IEEE 1588-2008), so is independent of GPS, and operates over either dedicated channels or PTP-compatible network routes.

NPL is participating in ESA's Atomic Clock Ensemble in Space (ACES) mission. Preparations are currently underway for the installation of an ACES MicroWave Link (MWL) ground terminal at NPL at the end of 2017 or early 2018. This will be linked to NPL's caesium fountain and optical clocks using high stability frequency distribution. NPL, with contributing funds from the UK Space Agency, is also investigating methods for analysing data from the ACES MWL.

NPL has had a leading role in designing a time scale for operation in the Square Kilometre Array (SKA) telescope, as part of a consortium led by the University of Manchester, UK. The time scale developed by NPL is expected to be implemented in Australia, and a second facility to a very similar design may be constructed in South Africa. The time scales are planned to operate as far as possible automatically, and are based on many aspects of NPL's own UTC(NPL) time scale.

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Ytterbium ion optical frequency standard

$^{171}Yb^+$ has two optical clock transitions that are studied at NPL: an electric octupole (E3: $^2S_{1/2} – ^2F_{7/2}$) transition at 467 nm and an electric quadrupole (E2: $^2S_{1/2} – ^2D_{3/2}$) transition at 436 nm. The E3 transition is the better of the two for creating a frequency standard as it is capable of lower instabilities (due to its natural linewidth of just a few nanohertz [4]) and also lower uncertainties from systematic shifts. The E2 transition, with its larger sensitivity to external fields, makes a better probe of the environment; systematic frequency shifts can be readily measured with the E2 transition and scaled down to apply to the E3 transition.

The optical frequency ratio E3:E2 was measured directly in 2014, along with the absolute frequencies of the E2 and E3 transitions relative to NPL-CsF2 [5]. The contribution to the total uncertainty from the ion's systematic shifts was 5×10^{-17} for the E3 transition and 3×10^{-16} for the E2 transition. In both cases, uncertainty in the differential atomic polarisability of the transition led to the blackbody radiation shift dominating the uncertainty budget. New polarisability measurements have now been carried out, recording the atomic frequency shift induced by the electric field from a 7-µm laser for both the E2 and E3 transitions. Preliminary results give an improved value for the E2 polarisability, and also show good agreement with PTB's recent measurement for the E3 polarisability [6]. The total uncertainty from the ion's systematic frequency shifts should now be below 10^{-16} for the E2 transition and below 10^{-17} for the E3 transition.

The new end-cap ion trap, "Yb^+ Trap 3", has been characterised [7, 8], with an uncertainty contribution from all the trap-based frequency shifts at the 4×10^{-19} level for the E3 transition. The motional heating rate of the ion was measured to be 24 ± 30 quanta/s via the dephasing of Rabi flops. The effective temperature rise at the ion was determined via a combination of thermal imaging and finite element modelling to be $\Delta T = 0.14 \pm 0.14$ K, limited by the rf loss in the vacuum feedthrough.

Direct comparisons with optical frequency standards at other European NMIs have been made via satellite links. In October 2014, the $^{171}Yb^+$ (E2) frequency standard was compared with PTB via a GPS-PPP data analysis technique [9], and in June 2015, the NPL Yb^+ (E3) frequency standard was run during a campaign linking NPL, PTB, LNE-SYRTE and INRIM via broadband two-way satellite time and frequency transfer (EMRP project ITOC). Analysis of the June 2015 Yb^+ data, linked to UTC(NPL) and UTC, has provided an absolute frequency measurement of Yb^+ (E3) relative to an ensemble of primary standards contributing to Circular T. With a fractional uncertainty of 4×10^{-16}, this new measurement is competitive with the best Yb^+ absolute frequency measurements against local caesium fountains.

Future plans include reducing the linewidth of the clock laser to allow longer probe times and hence lower instabilities. The NPL Yb^+ standard will also be measured against optical standards at PTB and LNE-SYRTE via optical fibre links to allow more stringent frequency comparisons and tests of fundamental physics.

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Strontium ion optical frequency standard

The 5s $^2S_{1/2}$ – 4d $^2D_{5/2}$ electric quadrupole transition at 445 THz (674 nm) in $^{88}Sr^+$ has a narrow natural linewidth of 0.4 Hz, and the ion can be laser-cooled and probed with commercially available diode laser technology. At NPL we have developed two Sr^+ endcap trap systems which have been compared and shown to have a null offset at the 4 parts in 10^{17} level [10]. Modelling of the frequency noise in our system has included the effect of magnetic field variations [11] which add to the overall level of white frequency noise, even in cases where the magnetic field noise character itself is not white. Reduced frequency instability and frequency shifts can arise from significant levels of micromotion [12] and ion heating. However, we plan to replace both our current traps with a new trap design initially developed at NPL for the ytterbium ion project. This is expected to provide reduced ion heating rates and allow us to reduce the micromotion to lower levels than in our current arrangement.

We have used two-trap comparison data together with AC Stark shift theory [13] underlying the calculation of the blackbody shift, to calculate the Stark shift as a function of laser wavelength from 350 nm to 10 μm and also verified at the 3% level the calculated shift at 1064 nm using a fibre laser [14].

In addition to building new traps, work is ongoing to upgrade a number of our laser systems. We have already implemented a lock of our 674-nm clock laser to our fs comb-based "universal synthesiser". This derives its stability from a 1064 nm YAG laser locked to a long ULE cavity. We have also implemented two waveguided frequency doublers; one provides output at 461 nm for photo-ionisation and another outputs 422 nm for laser cooling. Of the six lasers required for photo-ionisation and cooling, only two (at 844 nm and 674 nm) are now large extended cavity diode lasers. We are also investigating the feasibility of replacing these with alternative technologies with the longer-term aim to develop a compact and transportable system.

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Neutral strontium optical lattice frequency standard

A Sr optical lattice clock (NPL-Sr1) is in operation at NPL [15]. The clock operates on the $5s^2\ ^1S_0$ – $5s5p\ ^3P_0$ spin and angular momentum forbidden electronic transition at 429 THz in ultracold Sr. A conventional two-stage magneto-optical-trap is used to prepare micro-kelvin samples of Sr suitable for loading into a vertical 1D magic-frequency optical lattice trap at 368 THz, where the clock interrogation takes place free of recoil and Doppler related frequency shifts. NPL-Sr1 has the capability to trap and interrogate both fermionic ^{87}Sr and bosonic ^{88}Sr isotopes.

The system has demonstrated good reliability, contributing 502 hours of ^{87}Sr measurement data (uptime of around 83%) to the International Timescales for Optical Clocks satellite comparison campaign (EMRP project ITOC). Following this campaign further systems have been put in place to ensure reliable operation without human intervention. An evaluation of all known shifts has since been completed and a preliminary estimate of the total systematic uncertainty is at the low parts in 10^{17} fractional frequency. The contribution from BBR radiation, the leading systematic shift, was reduced to 1 part in 10^{17} by controlling the temperature gradients across the chamber.

To characterise the DC Stark shift, an inability to induce a measurable shift by application of an external electric field led us to a novel electrometry using electromagnetically induced transparency (EIT) spectroscopy of Rydberg states. The method required only a single additional laser at 413 nm to pump atoms from the $5s5p\ ^1P_1$ state to $5s75d\ ^1D_2$, with EIT probe at 461 nm at the position of the lattice trapped atoms. By observing the splitting of the $^1D_2$ m_J states we could constrain the fractional frequency uncertainty of the shift to 2 parts in 10^{20} [16].

Key to improving the systematic evaluation of the clock has been reducing the instability of interleaved self-comparisons. Using a universal synthesiser arrangement which transfers the stability of an ultrastable laser at 1064 nm to 698 nm across a femtosecond frequency comb via the transfer oscillator scheme, we have reduced the interleaved instability by a factor of three to 2 parts in $10^{15}\ \tau^{-1/2}$, shortening the required averaging time to a given instability by almost an order of magnitude.

With a view to the boson, a modified hyper-Ramsey method with cancellation to-all-orders of probe synchronous shifts was conceived and experimentally investigated using the magnetically-induced $5s^2\ ^1S_0$ – $5s5p\ ^3P_0$ transition in ^{88}Sr. An automatic suppression of sizeable 2 parts in 10^{13} probe Stark shifts to below 1 part in 10^{16} was demonstrated even for very large uncompensated shifts [17]. The scheme has applicability to other highly forbidden transitions such as the Yb^+ E3.

Recently, NPL-Sr1 was compared to two Sr clocks in SYRTE over an 800 km dark fibre link operated between NPL and LPL and LPL to SYRTE. The comparison reached a fractional frequency instability of a few parts in 10^{17} after 10^4 s of averaging, limited by the performance of the clocks. Data from the comparison has been used to perform a novel test of special relativity exploiting the diurnal variations in the frequency difference of remote clocks. The analysis further constrained the Robertson-Mansouri-Sexl parameter which describes potential deviations from Lorentz invariance (see [26]). Further comparisons are planned within the EMPIR project OFTEN.

Absolute frequency measurements of both ^{87}Sr and ^{88}Sr together with local optical frequency ratios against Yb^+ and Sr^+ clocks are currently being pursued. The lab is also involved in the EMPIR OC18 project. A second Sr lattice clock system is under construction.

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EMPIR OC18 project "Optical clocks with 1×10^{-18} uncertainty"

NPL is coordinating the EMPIR-funded project "Optical clocks with 1×10^{-18} uncertainty" (OC18), which aims to develop world-leading optical atomic clocks across Europe that can reach an uncertainty of 1 part in 10^{18} after just a few hours of statistical averaging.
The project therefore requires advances in many aspects of optical clocks including laser stabilisation, atom traps, control of systematic frequency shifts and novel probing techniques. Much of NPL's progress in these activities has been described already in this report, in the separate sections for each optical clock system.

One of the overall goals of the project is to validate that the clocks perform at their target uncertainties through direct frequency comparisons between two independent systems. NPL will be participating in both intra- and inter- species comparisons, using femtosecond frequency combs to compare the local ^{87}Sr, $^{171}Yb^+$ and $^{88}Sr^+$ standards. It is also hoped to compare these standards with others in Europe via optical fibre links as part of the EMPIR-funded project "Optical frequency transfer – a European network" (OFTEN). Such measurements will demonstrate the reproducibility of the standards and give confidence in the frequencies used to derive recommended values for the secondary representations of the SI second.

Femtosecond optical frequency combs

NPL currently operates three femtosecond optical frequency combs. The first (NPL-FC1) is based on a Kerr-lens mode-locked Ti:sapphire laser with a repetition rate of approximately 90 MHz. The second (NPL-FC3) is based on a femtosecond erbium-doped fibre laser with a repetition rate of around 100 MHz and is designed to be readily transportable, so that it can be used for measurements away from the NPL site (see ITOC section below). The third (NPL-FC4) is an erbium-doped fibre comb with a repetition rate of around 250 MHz, and has a set of high-power narrow-band frequency comb outputs centred on the wavelengths of interest for our optical clocks. For frequency measurements on the NPL site, the combs are referenced to one of our hydrogen masers. Traceability to the SI second is provided either by our local caesium fountain primary frequency standards or by linking to International Atomic Time (TAI).

Absolute frequency measurements and optical frequency ratio measurements are made using the transfer oscillator scheme [18]. The accuracy of our measurement systems have been evaluated by comparing two independent frequency combs (NPL-FC1 and NPL-FC2) [19]. with agreement at the 5×10^{-18} level for absolute frequency measurements and agreement at the 3×10^{-21} level for optical frequency ratio measurements. The technical details presented in reference [19] underpin recent absolute frequency measurements and optical frequency ratio measurements performed at NPL [5, 10]. The femtosecond combs have also been used to support international optical clock comparisons via satellite links [9] and fibre links (see [26]), as well as the CCL-K11 key comparison of optical frequency and wavelength standards [20].

NPL-FC4 forms the heart of a "universal frequency synthesizer" that we are using to provide a single higher stability reference source to replace a number of frequency-specific individual local oscillators used for NPL's optical atomic clocks and caesium fountain primary frequency standards. Referenced to a 1064 nm ultrastable laser system, this system can provide both high stability optical signals suitable for probing our optical atomic clocks and high stability microwave signals suitable for use as local oscillators for our caesium fountains. It can also be used to make absolute frequency measurements and optical frequency measurements, opening up the possibility of comparing more than two standards simultaneously, and to transfer the stability of the optical atomic clocks to the 1.5 µm region for frequency comparisons using optical fibre networks. The excess frequency instability introduced by the frequency comb NPL-FC4 has been characterized by making out-of-loop measurements using a second, independent, fibre comb (NPL-FC3), and the performance was found to be better than previously reported for multi-branch combs. Improvements to the design of the beat detection units are currently being implemented to explore the ultimate limits to performance. Remote monitoring and control systems are also being developed with the aim of being able to operate the universal frequency synthesizer continuously and autonomously for extended periods of time (many days).

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EMRP ITOC project "International timescales with optical clocks"

NPL coordinated the EMRP-funded project "International timescales with optical clocks" (ITOC), which ran from May 2013 to April 2016 and which aimed to tackle some of the key challenges that must be addressed prior to an optical redefinition of the second [21, 22].

A major part of the project involved the development of improved methods for comparing optical clocks, with emphasis on techniques that could be employed on an intercontinental scale. In June 2015 a 26-day international clock comparison campaign was performed using a broadband version of two-way satellite time and frequency transfer (TWSTFT). This involved four European NMIs (NPL, PTB, LNE-SYRTE and INRIM), with at least one optical clock running in each laboratory, as well as caesium fountain primary frequency standards. Link uncertainties in the low parts in 10^{16} range were reached, approximately an order of magnitude better than achieved using the standard TWSTFT currently used to compare microwave clocks for the computation of TAI and UTC. The recently introduced GPS integer precise point positioning (IPPP) technique was also shown to have similar performance to broadband TWSTFT, but with the significant advantage that it is a considerably cheaper and more robust technique that can readily be put into regular operation.

Relativistic effects affecting optical clock comparisons were evaluated at the 10^{-18} level of accuracy, compatible with the projected uncertainties of the clocks. NPL contributed to this work by evaluating the relativistic corrections relevant to the broadband TWSTFT experiment discussed above. We also collaborated with researchers from the Institut für Erdmessung (IfE) at the Leibniz Universität Hannover (LUH) to determine the gravity potential at the locations of the European optical clocks with the best possible accuracy. They performed gravity surveys at the various clock sites, including two absolute gravity observations on the NPL site and 63 relative gravity observations around the NPL site. A new European quasi-geoid model was then computed, incorporating the new gravity measurements carried out at and around NPL and the other NMI sites. This has unified the description of the geopotential for the European NMIs presently operating high accuracy optical atomic clocks (INRIM, LNE-SYRTE, NPL and PTB).

Within the project, NPL developed new methods and procedures for analysing over-determined sets of clock frequency comparison data based on a number of different reference transitions [23, 24]. Our least-squares adjustment procedure, which is based on the method used by CODATA to derive a self-consistent set of values for the fundamental physical constants, can be used to derive optimized values for the frequency ratios of all possible pairs of reference transitions (including absolute frequencies as a special case). Our methods were used by the CCL-CCTF Frequency Standards Working Group in September 2015 in updating the list of CIPM recommended frequency values, and are being used again in 2017.

NPL also participated in a proof-of-principle experiment carried out within the ITOC project, which aimed to demonstrate that the gravitational redshift of optical clocks can be exploited to measure gravity potential differences over medium-long baselines [25]. For this experiment a transportable strontium optical lattice clock from PTB was taken to the Laboratoire Souterrain de Modane (LSM) in the Fréjus tunnel between France and Italy. There it was compared with clocks at INRIM using an optical fibre link. Since no frequency comb is available at LSM, the transportable femtosecond comb from NPL was used to link the frequency of the Sr clock laser to the frequency of a 1.5 µm transfer laser transmitted over the optical fibre link from INRIM. This work, performed in collaboration with PTB and INRIM,

demonstrates the future benefits that measurements of this type could bring to the geodesy community.

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Fibre transfer

NPL continues to operate the 800 km **dark fibre link between NPL and LPL (France)**, jointly with LPL and SYRTE. The link is equipped with remotely-controlled bidirectional optical amplifiers in 10 locations and an optical round-trip phase detection technique is used for the suppression of the environmentally-induced noise in the fibre. The link was successfully used in a comparison of Sr lattice clocks between NPL and SYRTE in June 2016 which achieved a fractional frequency instability of a few parts in 10^{17} after 10^4 seconds, limited by the performance of the clocks.

Data from the comparison has been used to perform a **novel test of special relativity** [26], which relies on detecting diurnal variations in the frequency difference of remote clocks. The analysis established a new upper bound for the Robertson-Mansouri-Sexl parameter which describes potential deviations from Lorentz invariance, roughly a factor of two lower than previous experiments.

The above clock comparison campaign was one of a number of campaigns scheduled as part of EMPIR project **"Optical Frequency Transfer – a European Network (OFTEN)"**, which runs from June 2016 to June 2019. Together with the link between PTB (Germany) and SYRTE, simultaneous three-way optical clock comparisons are now possible and are planned within OFTEN. Also within OFTEN, NPL is leading the development of a framework for fast and accurate Cs fountain comparisons, using an extended network of both optical carrier and rf-over-fibre links. The goal is to run links continuously with standardised and automated sharing of data, enabling "on demand" clock comparisons across the network without the need to involve multiple intermediate partners.

NPL is also contributing to a new European Horizon 2020 project **"CLOck NETwork Services – Strategy and Innovation for clock services over optical-fiber networks"**, running from January 2016 to June 2019. The project aims to strengthen the coordination between research infrastructures and the research and education telecommunication networks, as well as to help transfer fibre-optic time and frequency technology to industry, in order to prepare the ground for a sustainable, pan-European network providing high-performance "clock" services. In a first step, NPL will be surveying European research infrastructures and research organisations from a broad range of scientific fields for their current and future time and frequency needs.

NPL has also continued work on the dissemination of optical frequency combs through optical fibre links and demonstrated time transfer with an accuracy of 100 ps over 159 km (NPL to Reading loop). Following previous frequency transfer results, with this latest work NPL has shown that time and frequency (both microwave and optical) can be disseminated simultaneously using a pulse train at a level suitable for state-of-the-art metrology [27].

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