Report from NPL to the 20th session of the Consultative Committee for Time and Frequency (CCTF), 2015

Microwave frequency standards

NPL operates three microwave frequency standards based on the cold atom fountain technology, two using caesium and one using rubidium.

The caesium fountain primary frequency standard NPL-CsF2 was first characterised in 2009 [1] and has since contributed 55 times to the BIPM steering process of TAI. Its type B uncertainty was reassessed at a lower level in 2011 [2] and then again in 2013 at 2×10^{-16} when a new analysis was performed of the frequency shift due to collisions with the background gas [3]. In addition to the regular TAI evaluations, the standard NPL-CsF2 was used as a reference for in-house absolute frequency measurements of optical transitions and for an independent measurement of the ^{87}Rb microwave clock transition.

Another caesium fountain setup, designated as NPL-CsF3, was made operational in 2014. It was built using some parts of a decommissioned system NPL-CsF1. NPL-CsF3 functions in a similar fashion to NPL-CsF2, with a single stage MOT cold atom source and optical pumping to m_F=0 sublevel to boost the detected atom number. As in NPL-CsF2, the collisional shift and its uncertainty is minimised by operation near the cancellation point [4]. A major novelty of the new fountain is a microwave Ramsey cavity, which is designed to minimise the longitudinal phase gradients of the interrogating field [5]. A full accuracy evaluation of NPL-CsF3 is currently underway. A trial run using a new local oscillator utilising an optical source and a frequency comb to generate stable microwave signal has demonstrated a short-term stability at 3.7×10^{-14} (1 s).

The rubidium fountain frequency standard was fully characterised in 2011 [6]. Three measurement campaigns were performed between 2009 and 2013 [7] and the value of the Rb clock transition obtained with NPL-CsF2 as a reference was found in a good agreement with earlier measurements by SYRTE. Such independent verification of the Rb clock frequency has been desirable as the CCTF recommended value for this secondary representation of the second was based on measurements performed by one group only. The NPL Rb fountain has recently undergone modifications to its vacuum setup and has been suspended from a regular operation.

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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 octupole 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 [8, 9]) 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. A further advantage of having both the E3 and E2 optical clock transitions in $^{171}Yb^{+}$ is that they enable tests of fundamental physics. For example, the two transitions have large and different sensitivities to the value of the fine structure constant α, and any fractional change in α leads to a nearly seven-fold greater fractional change in the ratio of the E3:E2 optical frequencies.

Recent changes to the hardware and software controlling the experiment at NPL have enabled both the E3 and E2 transitions to be probed at the same time, in an interleaved manner, in a single ion of $^{171}Yb^{+}$ [10]. This allowed the direct optical ratio to be measured, f(E3)/f(E2) = 0.932 829 404 530 964 65(31). The absolute frequencies of both transitions were also measured simultaneously against the caesium fountain NPL-CsF2, yielding f(E3) = 642 121 496 772 644.91(37) Hz and f(E2) = 688 358 979 309 308.42(42) Hz. The absolute frequencies both had total uncertainties at the 6×10^{-16} level, limited by the Cs statistics, whereas the direct ratio was free from the instability introduced by the Cs fountain and had a total uncertainty of 3×10^{-16}. For the E3 transition, the contribution to the total uncertainty from the ion's systematic shifts was just 5×10^{-17}, an order of magnitude improvement from NPL's previous measurement [11]. These new results, combined with a history of absolute measurements in other optical frequency standards, enabled us to place an improved constraint on the level of present-day time variation of the fine structure constant of $\dot{\alpha}/\alpha = -0.7(2.1) \times 10^{-17}$ /year, and a x3 improvement in the constraint on time-variation of the proton-to-electron mass ratio at the level of $\dot{\mu}/\mu = 0.2(1.1) \times 10^{-16}$ /year.

The absolute frequencies agreed well with those measured independently at a similar level at PTB [12, 13], leading to the best international agreement between ion optical frequency standards. Recently, more direct comparisons between optical frequency standards at other European NMIs have been made via satellite and optical fibre links. In October 2014, both PTB and NPL ran their $^{171}Yb^{+}$ (E2) frequency standards at the same time and performed a PPP analysis of GPS data to establish a relative frequency difference between the two optical standards of $-1.3(1.2) \times 10^{-15}$ [14]. 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, and in the latter part of June 2015 the NPL optical frequency standards were also linked via optical fibre to LNE-SYRTE.

Recent changes to the experimental setup have included building a new ion trap with reduced thermal and motional heating rates, which can be housed within two layers of mu-metal for increased shielding from external magnetic fields. The frequency doubling crystal in a build-up cavity that was used to generate 467 nm light has been replaced with a more stable waveguide doubler, and evaluation of the ac Stark shift from this light has been improved through faster extrapolation of the frequency shifts to zero power and real-time monitoring of the stabilised probe power. Future plans include reducing the linewidth of the clock laser, to allow the possibility of longer probe times and hyper-Ramsey pulse sequences.

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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 [15]. This corresponds to a single trap reproducibility of 3 parts in 10^{17}. This reproducibility underpins the NRC projected uncertainty budget [16] at the low parts in 10^{17} level. Using one of our two traps, we have also measured the frequency of the ^{88}Sr$^+$ 674 nm clock transition referenced to the NPL caesium fountain primary frequency standard to be f = 444 779 044 095 486.71(24) Hz. We have also recently participated in the European-wide EMRP frequency intercomparison within the ITOC project. For this study, we implemented significant software and hardware changes to produce an optical output and real-time correction of the frequency against the ^{88}Sr$^+$ clock transition. These changes will eventually also allow us to lock our clock laser to a fs comb “universal synthesiser”; this derives its stability from a 1064 nm YAG laser locked to a long ULE cavity.

A recent study of frequency noise in our system [17] has shown that we can explain the frequency instability as a combination of laser frequency noise, quantum projection noise and magnetic field noise. This latter noise source, which had not previously been studied, contributes to the white frequency noise even in cases where the magnetic field exhibits flicker noise or random walk. Modelling has shown good agreement with the observed instability and allows us to predict the level of magnetic shielding required in a future trap design. We are planning to implement recent trap design improvements which have been tested using our ytterbium ion optical clock. Results with the new trap design indicate much lower and more stable micromotion levels that will lead to improved frequency stability and reproducibility. The new trap design has also allowed demonstration of lower heating rates in Yb$^+$, which we also expect to be able to observe in ^{88}Sr$^+$. In combination with optical ground state selection, this should allow demonstration of excitation into the clock transition with near 100% probability, giving optimised trap stability. We have reported algorithms for the automatic minimisation of ion micromotion [18] that have been implemented in addition to those which monitor and relock the cooling and clock lasers [19]. We are planning to implement new pig-tailed frequency doublers for both our cooling and photo-ionisation laser systems which will lead to further improvements in the reliability of the strontium ion optical frequency standard.

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Neutral strontium optical lattice frequency standard

A Sr optical lattice clock is now in operation at NPL, known as NPL-Sr1. The clock operates on the $5s^2\,{}^1S_0 - 5s5p\,{}^3P_0$ spin and angular momentum forbidden electronic transition in Sr at 429 THz. A two-stage magneto-optical-trap is used to prepare micro-kelvin samples of Sr suitable for loading into a 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 system has the capability to trap and interrogate both the fermionic isotope ^{87}Sr, and bosonic ^{88}Sr.

In a recent measurement campaign, International Timescales for Optical Clocks (EMRP project ITOC), NPL-Sr1, configured for ^{87}Sr, was operational for 502 hours (uptime of around 83%), during which a systematic frequency uncertainty below 2 parts in 10^{16} (~ 100 mHz) was obtained. Further characterisation of lattice stark shift will reduce this uncertainty to mid parts in 10^{17}. The contribution from the BBR shift is currently not limiting, with a combined uncertainty due to the line of sight to the atomic oven and the surrounding chamber at 2 parts in 10^{17}. This results from a small temperature inhomogeneity across the chamber of 0.8 K, which can be trivially reduced to 0.3 K with rearrangement of the water cooling apparatus to provide a BBR shift uncertainty at 5 parts in 10^{18}.

A clock self-comparison demonstrated a stability of 6 parts in $10^{15}\,\tau^{-1/2}$ limited by aliasing of clock laser noise due to the Dick effect. Clock spectroscopy has revealed a laser-limited linewidth of 9 Hz, corresponding to a quality factor of ~ 5 x 10^{13}.

Future efforts will focus on increasing the achievable quality factor and therefore clock stability through an improved local oscillator. A total uncertainty of the ^{87}Sr clock below 1 part in 10^{17} should then be achievable. 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.

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 around 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, with a GPS-disciplined oscillator that can be used as a frequency reference for measurements made away from the NPL site. The third (NPL-FC4) is a fibre-based comb with a repetition rate of around 250 MHz, and has a set of high-power narrow-band frequency comb outputs centred on wavelengths of interest for our optical clocks. For frequency measurements on the NPL site, the combs are referenced to one of our hydrogen masers, which for the most accurate frequency measurements are referenced to the NPL caesium fountain primary frequency standard NPL-CsF2.

Absolute frequency measurements and optical frequency ratio measurements are made using the transfer oscillator scheme [20]. The accuracy of our measurement systems have been evaluated via a series of comparisons between two independent femtosecond frequency combs (NPL-FC1 and NPL-FC3) [21]. Simultaneous measurements performed using the two systems showed agreement at the level of 5×10^{-18} when measuring an optical frequency against a common microwave reference. When simultaneously measuring the ratio of two optical frequencies, agreement at the 3×10^{-21} level was observed. These results represent the highest reported level of agreement to date between Ti:sapphire and Er-doped fibre femtosecond combs. The technical details presented in reference [21] underpin recent absolute frequency measurements of the $^{171}\mathrm{Yb}^+$ [10] and $^{88}\mathrm{Sr}^+$ [15] optical clock transitions at NPL, as well as a frequency ratio measurement between the two optical clock transitions in $^{171}\mathrm{Yb}^+$ [10]. The femtosecond combs have also been used in an international comparison of $^{171}\mathrm{Yb}^+$ optical clocks at PTB and NPL via a GPS PPP link [14].

Work has also been undertaken on the generation of ultra-low-noise microwave signals from optically referenced femtosecond combs, within the framework of the EMRP-funded project IND14, “New generation of frequency standards for industry”. To overcome problems of amplitude to phase noise conversion in photodetectors, we have focussed on extraction techniques based on balanced optical-microwave phase detection. Through improvements to previously reported designs [22], we have reduced the contribution of amplitude noise to the phase noise of the extracted microwave signal by 6 orders of magnitude [23]. This represents an improvement of a factor of 300 over previously reported results using the same technique, and enables the technique to be used for the extraction of low noise microwave signals from commercial mode-locked lasers with relatively high levels of residual intensity noise.

NPL-FC4 forms the heart of a “universal frequency synthesizer” that we are developing 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 state-of-the-art 1064 nm ultrastable laser system, this universal synthesizer will 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 will 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 remote frequency comparisons using optical fibre networks. The aim is that the system should be capable of operating continuously and autonomously for extended periods of time (many days).

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EMRP project “International timescales with optical clocks”

NPL is coordinating the EMRP-funded project “International timescales with optical clocks” (ITOC), which aims to tackle some of the key challenges that must be addressed prior to an optical redefinition of the second [24, 25].

A major part of the project involves 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 three-week 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. Local optical frequency comparisons were also performed at NPL during the campaign, and data analysis is currently underway.

The relativistic effects influencing comparisons between clocks are being evaluated at an improved level of accuracy. NPL has contributed to this work by evaluating the relativistic corrections relevant to the broadband TWSTFT experiment discussed above. We have 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 have 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. Now all gravity surveys have been completed, the measurements are being used to compute a revised model of the European geoid. Tidal effects have also been calculated.

Within the project, NPL has developed for analysing over-determined sets of clock frequency comparison data involving standards based on a number of different reference transitions [26]. 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). The key issues encountered in assessing an over-determined set of frequency comparison data have been identified, and are likely to be highly relevant to future discussions within the CCL-CCTF Working Group on Frequency Standards.

NPL will also participate in a proof-of-principle experiment being carried out within the ITOC project, which aims to demonstrate that the gravitational redshift of optical clocks can be exploited to measure gravity potential differences over medium-long baselines. The two optical clocks used in this experiment will be the INRIM ytterbium optical lattice clock and a transportable strontium optical lattice clock from PTB, which will be taken to the Laboratoire Souterrain de Modane (LSM) in the Fréjus tunnel between France and Italy. The frequency comparison between the two clocks will be performed using an optical fibre link, with two optical frequency combs being required to transfer the stability of the optical clocks to the 1.5 µm fibre transmission window. Since no frequency comb is available at LSM, the transportable femtosecond comb from NPL will be used. The INRIM-LSM test-bed offers a large gravity potential difference, with a height difference of approximately 1000 m between the two sites, corresponding to an expected gravitational redshift of about 10^{-13}. Preparation of the experimental subsystems is underway and the experiment itself is scheduled towards the end of 2015.

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Fibre transfer

We have installed one of the first international optical fibre links for the comparison of state-of-the-art optical clocks. A 800 km-long dark fibre (part of the GÉANT European Research and Education Network) link between NPL and LPL (France) was equipped with remotely-controlled bidirectional optical amplifiers in 8 locations and an optical round-trip phase detection technique was used for the suppression of the environmentally-induced noise in the fibre. The first fibre-based comparison of the NPL and SYRTE optical clocks, via the LPL laboratory, was performed in July and the collected data is being analysed at the time of writing. The newly implemented fibre link enables the comparison of atomic clock at a level orders of magnitude better than what is currently achievable with microwave satellite links.

Building on previous work on the dissemination of optical frequency combs through optical fibre links, we have demonstrated a novel time transfer technique based on the propagation of a pulse train from a mode-locked laser. A time deviation below 1 ps over time scales from 1 s to many 1000s s and a time accuracy of 80ps was demonstrated over 50 km fibre spool. Tests are currently underway to replicate these results on a 158 km installed fibre link.

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 [27]. As of July 2015, the UTC(NPL) time scale was based on an group of four active hydrogen masers and three commercial caesium clocks. A replacement high-performance 5071A caesium clock was purchased in summer 2015 and an additional maser has been ordered from T4Science, with delivery expected 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 taken directly from one maser that is adjusted in frequency every few months to maintain alignment with UTC, but work is in progress to generate it instead using a frequency offset generator steered daily to caesium fountain measurements or UTCr results.

NPL operates both of the standard methods for performing regular time and frequency comparisons with other timing institutes. The primary two-way satellite time and frequency transfer (TWSTFT) earth station has not operated for some time due to equipment failures and relocation to a different building, but is expected to be back in regular operation by September 2015. A second Earth station was assembled for the 20 Mchip/s TWSTFT measurement campaigns carried out in October 2014 and June 2015 as part of the EMRP project ITOC (International Timescales with Optical Clocks). The main GPS timing receiver at NPL is a Dicom GTR50 dual frequency carrier-phase receiver, designated NP11, and two additional geodetic-quality GTR51 receivers and two single-frequency 8-channel GPS common-view receivers made by Time and Frequency Solutions Ltd are available as backup systems.

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 can provide direct and continuous traceability between a remote reference clock and UTC(NPL) with an uncertainty of better than 20 ns. NPL also operates two services that disseminate time to computers: a dial-up service utilising the European telephone time code, and NTP internet time servers. Frequency standards and GPS-disciplined oscillators can be calibrated at either NPL or a customer's site.

A new service known as NPL*Time*® has been developed for time distribution over optical fibres to the financial sector and other organisations. The service is resilient, traceable to UTC, and is monitored, managed and certified by NPL. 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 has been involved in the procurement from ESA (using committed UK Space Agency funding) of an Atomic Clock Ensemble in Space (ACES) MicroWave Link (MWL) ground terminal. Planning is currently underway for installation of the terminal at NPL, which is expected in 2016. NPL has also been investigating data analysis methods for some aspects of the MWL in collaboration with other ACES partners.

NPL has taken a lead in developing a time scale for operation in the Square Kilometre Array (SKA) telescope, as part of a consortium led by the University of Manchester. The aim is to design two near-identical time scales, one for operation in Australia and the other in South Africa. The time scales are planned to operate as far as possible automatically, and will be based on many aspects of NPL's own UTC(NPL) time scale.

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