Report from NPL to the 19th session of the Consultative Committee for Time and Frequency (CCTF), 2012

Microwave frequency standards

There exist three microwave frequency standards at NPL, two caesium fountains and one rubidium fountain.

The caesium fountain primary frequency standard, which is now in a regular use, is NPL-CsF2, rebuilt in 2008. The first accuracy evaluation of this standard was based on a measurement campaign performed in 2009 [1]. In this fountain, the zero-collisional shift operation approach has been adopted [2], which reduced the type B uncertainty of the density shift below one part in 10^{16}. A refined evaluation of the distributed cavity phase frequency shift and the microwave lensing effect [3] led to further improvement of the accuracy (total type B uncertainty of 2.3×10^{-16}, among the lowest of all primary frequency standards to date). In addition, the implementation of an optical pumping technique to accumulate atoms in the $m_F = 0$ clock state enabled a new operation protocol improving the effective short-term stability [4]. Since 2010, the standard has contributed 31 times to the steering process of TAI performed by the BIPM as well as provided reference for local absolute frequency measurements [5].

The primary standard NPL-CsF1, which contributed to the evaluations of the TAI scale interval between 2004 and 2007 [6], has recently been partially disassembled in preparation for a major refurbishment. The rebuilt fountain will operate in a similar fashion to the highly accurate standard NPL-CsF2 and its accuracy evaluation is expected to be performed in 2013. A system of two independent primary caesium standards will provide the necessary operational redundancy and enhance the construction of the local timescale UTC(NPL).

The accuracy of the rubidium fountain at NPL has been evaluated in 2011 [7]. Currently attempts are being made to perform an absolute measurement of the Rb ground state hyperfine splitting in support of the secondary representation of the second.

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Optical Frequency Standards

NPL has continued development of optical frequency standards based on narrow transitions in single cold trapped ions. Clock transitions in $^{88}Sr^{+}$ and $^{171}Yb^{+}$ are under study, namely the $^{2}S_{1/2} - ^{2}D_{5/2}$ electric quadrupole transition in $^{88}Sr^{+}$ and the $^{2}S_{1/2} - ^{2}F_{7/2}$ electric octupole and $^{2}S_{1/2} - ^{2}D_{3/2}$ electric quadrupole transitions in $^{171}Yb^{+}$. Additionally, NPL is building a neutral strontium atom lattice clock based on the $^{1}S_{0} - ^{3}P_{0}$ transition.

Ytterbium ion optical frequency standard

The lowest-lying excited state in $^{171}Yb^{+}$ decays to the ground state via an electric octupole transition at 467 nm, which has a natural linewidth in the region of a few nanohertz [8,9]. As a result, the stability of an optical frequency standard based on this transition will not in practice be limited by the natural linewidth of the clock transition, but rather by the probe laser linewidth that can be achieved and by the stability of external perturbations. The 467 nm transition in $^{171}Yb^{+}$ has furthermore been shown to have a particularly low electric quadrupole moment and relatively low atomic polarisability [10] which, combined with a first-order insensitivity to magnetic fields, leads to the ion being remarkably unperturbed by external fields.

By locking an ultrastable laser at 467nm to the octupole transition, with a linewidth of 10 Hz, the frequency was measured relative to NPL's caesium fountain primary standard NPL-CsF2. The resulting value was 642 121 496 772 646.22(67) Hz [11], which has a fractional accuracy of 1.0 x 10^{-15}, twenty times better than the previous measurement [12]. The result agreed with a similar measurement at PTB [10], leading to the best international agreement to date between ion optical frequency standards.

The 436 nm electric quadrupole transition $^{2}S_{1/2} - ^{2}D_{3/2}$ is also being studied at NPL and we have measured the frequency to be 688 358 979 309 310(9) Hz [13], also in excellent agreement with work carried out at PTB. Locking ultrastable laser light at 436nm simultaneously to the quadrupole transition in two separate single ions revealed stabilities at the few parts in 10^{16} level.

There have been many modifications to the experiment over the last three years to achieve these improved results. These have included: moving the apparatus to a new building with better environmental control, replacing Ar^{+} and Ti:sapphire lasers with more reliable all-diode systems, driving the clock transitions coherently, locking the clock lasers to the transitions rather than scanning their frequency, setting up phase noise cancellation on fibre links and spinning the polarisation of the cooling lasers to avoid the need for large magnetic fields at the ion. The next measurements will be repeated frequency ratios between the octupole and quadrupole transitions in order to place limits on any time variation of the fine structure constant.

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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 can be laser-cooled, and probed with commercially available diode laser technology. At NPL we have developed two Sr+ endcap trap systems Using one of them and a femtosecond optical frequency comb referenced to the NPL caesium fountain primary frequency standard, we previously measured the frequency of the $^{88}Sr^+$ 674 nm clock transition to be 444 779 044 095 484.6 (1.7) Hz [14,15]. Measurements using an NPL maser-referenced femtosecond comb yielded a value 444 779 095 482.2 (4.6) Hz [16] which is in good agreement with the previous value and an NRC value [17]. We have implemented optical pumping state selection for the ground state which has resulted in a factor of two increase in quantum jump rates. The presence of varying stray electric fields within the traps following ion loading has been an issue; the performance of our traps was significantly improved by using photo-ionisation rather than electron beam ionisation. Preparations are underway for a new optical frequency measurement; the uncertainty is expected to be better than 1 part in 10^{15}. A smaller compact Sr+ ring trap has been built demonstrating that is possible to reduce the volume of the current physics package by more than a factor of twenty; utilisation of a smaller pump has yielded more than a 5-fold weight reduction.

Using both endcap systems comparisons of the quadrupole 674 nm optical clock transitions in Sr^+ have demonstrated single-trap stabilities scaling with $\tau^{-1/2}$ reaching 2.5 x 10^{-16} at 4000 s. This was with 50 ms 674 nm probe laser interrogation pulses. Preliminary frequency comparisons between two traps indicate agreement at the 3 x 10^{-16} level on overnight data taking runs. A programme of hardware and software development has improved the reliability of the two-trap system [18]. The locks of the cooling and probe lasers can be monitored, with automatic recovery from out-of-lock conditions that occasionally arise. We can also automatically minimise the micromotion of the ion. This has allowed continuous unattended data taking periods of up to 2.5 days and paves the way for a reliable Sr^+ ion-trap-based optical standard capable of remote operation.

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Neutral strontium lattice clock

The current best absolute frequency measurement of the ^{87}Sr isotope clock transition in neutral Sr was made at JILA with an error of 8.6 x 10^{-16}, which is presently the most accurate measurement of any optical frequency standard based on neutral atoms. In addition, the systematic uncertainty of the lattice clock contribution to this measurement was only 1.5 x 10^{-16}. Measurements made during the past few years in Japan, the US, and France all agree at the part in 10^{15} level. This high level of reproducibility makes a strong case for the clock transition in neutral strontium to be adopted as the new definition for the SI second.

Barring the way to uncertainties at level better than a part in 10^{16} is the systematic error due to the shift of the clock frequency in the presence of blackbody radiation from the room temperature vacuum chamber surrounding the atomic sample (BBR shift). Only theoretical valves for this shift have been calculated. In order to make progress in reducing the overall uncertainly of Sr lattice clocks this frequency shift will need to be experimentally explored.

At NPL we are developing a lattice clock based on neutral strontium atoms. As part of the development stage we have designed [19,20], built and successfully tested a number of novel Zeeman slower designs. Standard Zeeman slowers use current flow in a solenoid to produce a varying magnetic field, which in conjunction with a counter-propagating single frequency laser beam is used to slow an atomic beam so that the atoms can be captured in a magneto-optical trap (MOT). We have shown that an array of permanent (neodymium) magnets creating a field either longitudinal or transverse to the atomic beam can efficiently and predictably slow the atomic beam. By using permanent magnets rather than current-carrying coils, we eliminate the need for (and noise from) power supplies and water cooling. Additionally, the Zeeman slower can be removed from the vacuum system for adjustment without breaking vacuum and its field can be fine-tuned in situ. We have characterized our permanent magnet Zeeman slower by directly measuring the velocity distribution of the slowed atoms and by trapping ~2 x 10^7 atoms in a 461nm MOT. A ULE-cavity-stabilised 2nd-stage cooling laser at 689 nm has also been developed with a linewith of < 1kHz, which has been used for atomic beam spectroscopy. A pair of vibration-insensitive vertical-cavity-stabilised clock lasers at 698 nm are under evaluation, with a preliminary result showing sub-200Hz linewidths.

One major goal of this project is to provide an experimental measurement of the blackbody radiation shift in neutral strontium. We have designed and built an experimental setup that will allow us to hold the atoms in a well-characterised and controlled environment while probing the clock transition. Microkelvin temperature atoms will be transferred from the centre of the vacuum chamber into a temperature stabilised copper tube (with graphite insert) via a moving lattice. The atoms will then be transferred into a standard magic lattice at 813 nm and held there during the clock spectroscopy. The sample will then be transported back out of the copper tube for measurement read-out. A second similarly controlled tube will be added to the vacuum chamber to allow us to perform a differential measurement of the black-body radiation shift in two differing thermal environments.

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Femtosecond optical frequency combs

NPL operates three femtosecond optical frequency combs. Two of these are based on Kerr-lens mode-locked Ti:sapphire lasers with repetition rates of around 90 MHz and 800 MHz. The third is based on a femtosecond erbium-doped fibre laser and is designed to be transportable, with a GPS-disciplined oscillator that can be used as a frequency reference for measurements made away from the NPL site [21]. For frequency measurements on the NPL site, the combs are referenced to one of the NPL hydrogen masers, which for the most accurate frequency measurements are referenced to the NPL caesium fountain primary frequency standard NPL-CsF2.

We have recently demonstrated a novel design of *f*:2*f* interferometer for stabilizing the carrier-envelope offset frequency of a Ti:sapphire frequency comb [22]. This simple and compact scheme uses a Wollaston prism for group-delay dispersion compensation, providing an all-common-path optical configuration that provides superior immunity to air currents and acoustic noise compared to the more commonly used Mach-Zehnder or Michelson interferometers. This type of interferometer has been implemented on both Ti:sapphire frequency combs at NPL.

Using NPL-CsF2 as a frequency reference, we have recently made a frequency measurement of the electric octupole clock transition in $^{171}Yb^+$ with an uncertainty of 1 part in 10^{15} [11]. The transition frequency was measured simultaneously using the lower repetition rate Ti:sapphire comb and the fibre comb, which were referenced to a common maser-referenced rf synthesizer. The values obtained using the two combs agreed to within one part in 10^{17}, demonstrating that the combs themselves introduce negligible uncertainty. The uncertainty introduced by the rf frequency distribution and synthesizers used with the comb were found to result in a mean systematic frequency shift of less than one part in 10^{16}. Improved comparisons between the two combs have also been carried out by using them to measure simultaneously the optical frequency ratio between two ultrastable lasers; in this second set of measurements agreement between the combs was at the part in 10^{18} level for averaging times of a few thousand seconds.

Work is also underway to generate ultra-low-noise microwave signals from optically referenced femtosecond combs. To overcome problems of amplitude to phase noise conversion in photodetectors, we are investigating extraction techniques based on balanced optical-microwave detection [23]. This work is being undertaken as part of the EMRP project IND14, “New generation of frequency standards for industry”.

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Frequency transfer over optical fibre

NPL has demonstrated the transfer of a microwave frequency by propagation of an optical frequency comb over 50 km of spooled fibre. The transfer stability was measured to be better than 5×10^{-15} at 1 s, a factor of two better than previously shown by a similar experiment at JILA [24], and preliminary results were already included in the previous report to the CCTF. The results of this experiment were later published in [25].

The microwave transfer experiment was subsequently performed on 86 km of installed optical fibre (JANET-Aurora network) in collaboration with the University of Southampton. The transfer stability was measured to be 5×10^{-15} at 1 s and 4×10^{-17} at 1600 s, corresponding to a timing jitter of 64 fs. This work was published in [26].

Building on these microwave transfer experiments, another experiment was designed to test, for the first time for a noise-cancelled fibre link, the the stability and accuracy of the individual optical comb modes, rather than just their frequency spacing. An optical frequency comb was propagated over 7.7 km of spooled fibre and the stability and accuracy of the comb modes was measured against an ultra-strable laser. The fibre noise detection was based on an optical detection technique rather than microwave detection, as it was the case for previous experiments. The stability and the accuracy were measured to be better than a few parts in 10^{18}. These results of this experiment were published in [27].

NPL also conducted experiments on the transfer of a single optical carrier on 118 km of installed fibre (JANET-Aurora network) in collaboration with the University College London. The measured stability was better than 3×10^{-16} at 1 s and 5×10^{-18} at 20,000 s. The accuracy was measured to be 3×10^{-18}.

NPL is a partner in the Euramet NEAT-FT project "*Accurate time/frequency comparison and dissemination through optical telecommunication networks*". As part of this project NPL will be investigating the transfer of time, rather than frequency, using optical frequency combs.

NPL has also secured funding for a optical fibre link which will connect the laboratory to the Harwell campus and the JANET-Aurora network (which links four universities in Southern England), opening new opportunities for collaborative work and advanced time and frequency transfer over fibre experiments.

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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. The UTC(NPL) time scale is based on an group of four active hydrogen maser frequency standards and three commercial caesium clocks. The masers are distributed in three laboratories in different parts of the NPL building and the time scale generation systems are duplicated to improve resilience. At present UTC(NPL) is based on one maser that is adjusted in frequency every few months to maintain alignment with UTC. Two alternative methods for generating the time scale have been investigated and evaluated over extended periods, one using an external frequency offset generator steered every 3 or 4 days to caesium fountain measurements, and the other using a clock ensemble algorithm based on a Kalman filter that is able to incorporate both maser and fountain results.

Additional work has been carried out to develop algorithms that predict clock behaviour, and the methods have been applied to GPS satellite clock prediction in collaboration with University College London.

NPL operates both of the standard methods to perform regular time and frequency transfer measurements with other timing institutes. A two-way satellite time and frequency transfer (TWSTFT) earth station operates continuously under automated control, and a second station is under construction. The primary GPS timing receiver is a Dicom GTR50 dual frequency carrier-phase receiver, which was calibrated during a campaign carried out by PTB in October 2010. Two single-frequency 8-channel GPS common-view receivers made by Time and Frequency Solutions Ltd are also in use as backup systems. Methods for performing time transfer over dark optical fibre are also being studied.

A range of NPL services disseminate time and frequency. The MSF 60 kHz standard frequency and time signal is the most widely used source of traceable time within the UK. Since April 2007 the signal has been transmitted from Anthorn radio station in north-west England. For users requiring greater accuracy, NPL operates a GPS common-view service that provides direct and continuous traceability between a remote reference standard 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 either at NPL or at a customer's site.

NPL has played an active part in the Galileo Timing Interface Working Group set up by ESA, and participates in other international committees such as the EURAMET time and frequency technical committee and ITU-R Working Party 7A.