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Introduction

This report summarises the activities of the National Physical Laboratory in the generation and dissemination of the UK time scale. The report is divided into sections on the primary standard, the time scale UTC(NPL), time transfer activities, services for dissemination of UTC(NPL), the NPL's contribution to the development of the Galileo global navigation satellite system, and activity in optical frequency standards.

Microwave Frequency Standards

NPL currently operates three laser cooled microwave frequency standards: two caesium fountains and one rubidium fountain.

The primary standard NPL-CsF1 was first evaluated in 2004 [1] and later reassessed in 2006 [2]. Since then the standard has been used several times to measure the duration of the TAI scale interval. Most recently, four contributions to the TAI evaluation were made covering 115 days in 2007. In November 2007 the NPL-CsF1 operation was halted and the device was moved to a new lab. Attempts to restart the system in 2008 showed the need for modifications to the physics package, which are planned in 2009 and 2010.

The second fountain, NPL-CsF2, was made operational for the first time in 2006. The work concentrated on studies of the collisional frequency shift at sub-microkelvin temperatures [3]. Strong variations of the frequency shift as a function of the clock state fractional populations were observed. Moreover a shift cancellation point was found for a particular composition of the clock states. The effect was studied both experimentally and theoretically and explained in detail in collaboration with groups at NIST (Gaithersburg) and PTB [4]. A further study on prospects of operating a caesium fountain at the zero-shift point [5] served as a basis for redesign and reconstruction of the NPL-CsF2 system in 2008. The standard has been operational again since November 2008 and is currently undergoing accuracy evaluation.

The aim of the rubidium fountain work at NPL is to provide a secondary representation of the second with very good short-term stability and to underpin the stability of the NPL timescale. The assembly of the physics package was completed in 2007 and tests of the cooling and launching systems were performed. The fountain uses a two-stage 2D-MOT/molasses loading system and as many as 10^9 atoms (^{87}Rb isotope) can be launched. Since 2008 the entire system is fully operational and accuracy evaluation is currently under way.

UTC(NPL) Time Scale

NPL is the only institute in the UK that contributes to the generation of UTC. The UTC(NPL) time scale is based on an ensemble of four active hydrogen maser frequency standards and three commercial caesium clocks. The time scale was relocated into the new NPL building in October 2006. The masers are situated in three locations and the time scale systems duplicated in a different part of the building for improved reliability.

Further work has been carried out to develop algorithms that predict clock behaviour, combine clocks into a composite time scale, and steer the composite time scale using inputs such as Circular T and primary frequency standard results. The algorithms have been utilised in NPL's contributions to the Galileo system time scale, and are also being applied to and evaluated on the NPL clock ensemble.

Time Transfer

NPL operates a range of time transfer systems that link NPL into the international network of timing institutes. A two-way satellite time and frequency transfer (TWSTFT) earth station operates continuously under automated control, performing measurements every 2 hours with a range of other NMIs, and a second station is under construction. The operational station was calibrated in September 2008 as part of a European campaign [6].

The primary GPS time transfer receiver, an Ashtech Z12-T, failed in December 2007, and a Dicom GTR50 carrier-phase receiver has subsequently been installed and calibrated as a replacement. A number of single-frequency 8-channel GPS common-view receivers (TimeTrace model, supplied by Time and Frequency Solutions Ltd)are also in use.

Time and Frequency Dissemination Services

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 (it was previously broadcast from Rugby). 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 are also calibrated either at NPL or at a customer's site.

NPL is an active participant in the EURAMET time and frequency technical committee. It has been involved in the international programme to benchmark and publish the capabilities of its services in the form of CMC tables, and in the preparation of roadmaps for the predicted development of time and frequency metrology.

Participation in the development of the Galileo Reference Time Scale

NPL is performing a major technical role in the development of the Galileo Time Service Provider, which will provide the link between Galileo System Time and UTC. This work includes development of clock and time transfer processing and pre-processing algorithms, steering and prediction algorithms, development of the uncertainty budget, and development and implementation of the majority of the software. Much of the work is built on previous clock and time transfer algorithm development work at NPL [7].

In addition NPL is developing the time scale algorithms for one of the two Galileo Precise Time Facilities, under a contract led by Kayser-Threde. NPL has written the algorithms to generate the Galileo system time scale from the ensemble of clocks in the PTF, including determination of the GPS-Galileo time offset parameter, and will also carry out end-to-end testing of the systems installed in the PTF [8].

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 $^2S_{1/2}$ – $^2D_{5/2}$ electric quadrupole transition in $^{88}Sr^+$ and the $^2S_{1/2}$ – $^2F_{7/2}$ electric octupole and $^2S_{1/2}$ – $^2D_{3/2}$ electric quadrupole transitions in $^{171}Yb^+$. Additionally, NPL is building a neutral strontium atom lattice clock based on the $^1S_0$ – $^3P_0$ transition. Frequency measurements of 2S- nS, nD transitions in a hydrogen beam at wavelengths 750 – 868 nm are also scheduled over the next year, which will contribute to an improved determination of the Rydberg constant.

(i) 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 on the 674 nm clock transition with commercially available diode laser technology. Using a femtosecond optical frequency comb referenced to the NPL caesium fountain primary frequency standard, previously we measured [9,10] the frequency of the 674 nm clock transition to be 444 779 044 095 484.6 (1.7) Hz. More recent measurements using an NPL maser-referenced femtosecond comb yielded a value 444 779 095 482.2 (4.6) Hz [11] which is in good agreement with the previous value and a previous NRC value [12]. A 674 nm probe laser pulse duration of 10 ms was typically used, resulting in a Fourier-transform-limited linewidth of about 200 Hz for the Zeeman components of the $^2S_{1/2}$ – 4d $^2D_{5/2}$ clock transition.

The linewidth of the 674 nm probe laser had been assessed previously by heterodyning two independently stabilized 674 nm lasers and compensating for the linear component of the ULE cavity drift by mixing the beat with the output from a ramped function generator. The beat linewidth was observed to be a function of the measurement time, increasing from 2 Hz at 3 s to 6 Hz at 300 s. Assuming white frequency noise and that the performance of both lasers is similar, this indicates an individual laser linewidth of 4.4 Hz at 30 s, which is typical of the time required to scan over a single Zeeman component of the clock transition. Using this probe laser arrangement to scan the $m_j = 1/2 \rightarrow m_j{}' = 1/2$ Zeeman component of the 5s $^2S_{1/2}$ – 4d $^2D_{5/2}$ clock transition, in 2 Hz frequency steps with 40 interrogation cycles of 100 ms probe pulse duration per step and compensating for the linear component of the ULE cavity drift, the cold ion clock transition linewidth observed was 9 Hz. This is consistent with the Fourier transform of a τ = 100 ms probe pulse [13]. Finally, a second separate trapped strontium ion frequency standard has been constructed, with the intention of evaluating systematic frequency uncertainties on the 674 nm optical clock transition by means of two-trap comparisons. Preliminary stability measurements between the two systems of 10^{-14} at 100 s for probe pulse times of 10 ms have been observed.

(ii) Ytterbium ion octupole and quadrupole clock transitions

The lowest-lying excited state in $^{171}Yb^+$ is the $4f^{13}6s^2\ ^2F_{7/2}$ state, which decays to the $4f^{14}6s\ ^2S_{1/2}$ ground state via the electric octupole transition at 467 nm, which has a natural linewidth in the region of a few nanohertz [14, 15]. 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 experimental arrangement for the NPL $^{171}Yb^+$ optical frequency standard has been described in detail elsewhere [16, 17]. Using a femtosecond optical frequency comb, the frequency of the 467 nm clock transition has been measured to be 642 121 496 772 657 (12) Hz [17], which is a factor of 50 more precise than the previous octupole transition frequency value [16]. The major contributions to the uncertainty of this result are the maser uncertainty, measurement statistics and the ac Stark shift which arises due to the high probe laser intensity required to drive the weak clock transition at a reasonable rate. Crucial to the reduction of the ac Stark shift is the probe laser linewidth. As this is reduced, the spectral intensity increases for fixed total intensity. This allows a reduction in total intensity whilst maintaining the same excitation rate, and thereby reducing the ac Stark shift on the clock transition. For sub-Hz laser linewidths it is expected that the ac Stark shift will no longer dominate the systematic uncertainty budget. Previous heterodyne beat measurements between light beams whose frequencies were independently stabilized to separate ULE cavities gave beat linewidths of about 5 Hz and 20 Hz for averaging times of 1 s and 100 s respectively. This latter linewidth corresponds well with the observed cold ion 467 nm octupole linewidth of < 40 Hz [17]. A second separate trapped ytterbium ion frequency standard is under construction, with the intention of evaluating systematic frequency uncertainties on the 467 nm octupole clock transition by means of two-trap comparisons.

$^{171}Yb^+$ also has an optical clock transition based on the $^2S_{1/2}$ (F=0) – $^2D_{3/2}$ (F=2, m_F=0) quadrupole transition at 435 nm, which has been studied extensively at PTB. It has a theoretical linewidth of ~ 3 Hz. Recently at NPL we have driven this transition for the first time using an extended cavity diode laser at 871 nm stabilized to a high finesse vibration-insensitive ULE cavity and single-pass frequency-doubled in $KNbO_3$ to 435 nm. The quadrupole clock transition frequency at 435 nm was measured using a femtosecond comb that was referenced to one of the NPL hydrogen masers. The value obtained was 688 358 979 309 310 (9) Hz, with the uncertainty corresponding to a fractional uncertainty of 1.3×10^{-14}. The results are being prepared for publication.

(iii) Neutral strontium lattice clock

There has been significant activity in recent years in neutral atom lattice clocks, whereby neutral atoms are held in a far-detuned lattice dipole trap during the clock interrogation cycle, and where the frequency of the lattice laser is such that the large ac Stark shift of both ground and excited states of the clock transition are equal and thereby cancel.. There are a number of different species under investigation as lattice clocks, and NPL has recently begun research on the $^1S_0 – ^3P_0$ transition in ^{87}Sr. This is already a secondary representation of the second, and is being pursued in a number of laboratories worldwide. Recent frequency measurements of this transition from three different laboratories located around the world agree to within 2 Hz, with uncertainties in the 10^{-15} range. Further frequency measurements need to be made and compared between various laboratories, and in-depth studies of systematic effects in the neutral strontium system (especially relating to the frequency shift due to blackbody radiation) are needed for full characterisation of the neutral atom clock. At NPL, we are building an experimental apparatus with a small physical footprint, low power consumption, and designed for the ready assessment of systematic frequency shifts such as the blackbody shift. To this end a novel Zeeman slower design has been developed [18], whose magnetic field is produced using an adjustable array of permanent magnets rather than conventional current-carrying wires. This method removes the need for power supplies and water-cooling, and has a (conservatively-designed) length of ~25 cm. Currently, we are preparing to trap and cool Sr atoms using 2-stage cooling at 461 nm and 689 nm. We are also developing a pair of diode laser systems (grating stabilized external cavity diode lasers), with a goal of sub-Hz linewidth for interrogation of the 698 nm clock transition. This will be achieved by Pound-Drever-Hall stabilisation to high-finesse, vibrationally insensitive, ULE Fabry-Perot vertical cavities, where the cavity vacuum housing is mounted on an active vibration stabilisation platform within a “quiet house”. The stability and linewidth characteristics of the stabilized laser systems will be probed by making optical heterodyne measurements between the two independent lasers.

Femtosecond comb metrology development and remote frequency transfer

NPL now operates three femtosecond optical frequency combs. Two of these are based on femtosecond pulse Ti:sapphire lasers with repetition rates of ~90 MHz and 800 MHz respectively. The third comb is based on a transportable erbium-doped fibre femtosecond laser system. For frequency measurements referenced to microwave standards, all combs can be referenced to NPL hydrogen masers, which in turn are referenced either to the NPL Cs fountain, or to UTC. Measurements can also be made away from the NPL site by using a GPS-disciplined oscillator as a reference. Work is underway to generate stable microwave frequencies from a comb operating in optical clock mode.

NPL has also started activity on high accuracy remote frequency comparison by fibre. Early work concentrated on fibre transfer of a 100 nm bandwidth of a frequency comb. The femtosecond comb used in this case is that based on the mode-locked erbium-doped fibre laser that generates sub-150 fs pulses with the spectral bandwidth of around 100 nm. The 100 MHz pulse repetition rate of this laser has been transmitted over 50 km of spooled single mode fibre, the chromatic dispersion of which is compensated by the insertion of a matched length of dispersion compensating fibre. Transfer of the 15th harmonic of the repetition rate has been demonstrated with excess fractional frequency instability below $5 \times 10^{-15} \tau^{-1/2}$ for averaging times between 1 s and 50 s, using active phase stabilization by means of a fibre stretcher. This excess noise level is a factor of two better than that previously obtained over a 7 km installed fibre link [19], where the stability was measured after the round trip rather than at the “user” end. Our reported stability is limited at present by the measurement noise floor and work is currently underway to improve this, prior to experiments on a real fibre network. More recently, work has started on experiments in which a cw optical carrier frequency is transferred over optical fibres.

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