Report from NPL to the 17th session of the Consultative Committee for Time and Frequency (CCTF), 14th – 15th September 2006

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.

1 Microwave Frequency Standards

The primary frequency standard NPL-CsF1 was fully evaluated in 2004 [1] and the evaluation has been reassessed recently [2].

Since the first evaluation the standard has been used four times, over periods of at least 30 days, to measure the duration of the TAI scale interval. During one of those periods the NPL-CsF1 participated in a simultaneous comparison of three remote fountain standards. The results of the comparison showed agreement of the NPL-CsF1 with one remote fountain within 1σ and with another remote fountain within 2σ ($\sigma = 2\times10^{-15}$ was the combined uncertainty of the comparison) [3]. The primary standard NPL-CsF1 has also served as an absolute reference for a measurement of an optical clock frequency in the $^{88}Sr^{+}$ ion [4].

Construction of a second fountain apparatus NPL-CsF2 was completed in 2005 and early measurements performed in 2006. So far the work on the NPL-CsF2 has concentrated on implementation of cooling in an optical lattice and on studies of the collisional frequency shift variations at sub-microkelvin temperatures [5].

Apart from the work on primary caesium standards, a rubidium fountain is being built at NPL aiming to provide a secondary representation of the second with high short-term stability. The construction of the physical package has been now completed and tests of cooling, launching and detection systems are underway [6].

2 Time Scale

The NPL time scale UTC(NPL) is based on an ensemble of three active hydrogen maser frequency standards and two commercial caesium clocks, with a fourth maser on order. One maser is located temporarily in the primary standards laboratory in the new NPL building to act as a local reference oscillator for the caesium fountain, and is not at present contributing to TAI. The phase differences between the standards in the clock ensemble are monitored continuously by two multi-channel phase comparators. The NPL atomic clocks, time scale generation and time transfer systems are in the process of being relocated to laboratories in the new NPL building.

NPL has continued its work on time scale algorithms, including the development of a clock ensemble algorithm [7], a clock predictor [8] and the development of a steering algorithm. The algorithms are designed to enhance NPL's own UTC(NPL) time scale; however the underlying principles have been applied to NPL's Galileo work.

3 Time Transfer

NPL operates a range of time transfer systems. A two-way satellite time and frequency transfer (TWSTFT) earth station operates continuously and a second station is under development. The GNSS systems include two geodetic-quality GPS time transfer receivers (an Ashtech Z12-T and a Javad Legacy) and four multi-channel GPS common-view receivers (Time and Frequency Solutions TimeTrace, which were designed in collaboration with NPL). The Ashtech receiver is registered as an International GNSS Service (IGS) station, NPLD.

Development work on the TWSTFT systems has included participation in an international calibration exercise [9]. GNSS research has focused on a continuing study of code and phase time transfer using GNSS systems, in collaboration with University College London. NPL is also supporting a student at Leeds University working on the development of new GNSS timing receivers.

4 Time and Frequency Dissemination Services

The MSF 60 kHz standard frequency and time signal, broadcast from Rugby Radio Station, remains the most widely used method of disseminating time and frequency within the UK. A contract for the operation of the service for a further 10 years from April 2007 has been awarded to VT Communications, and in consequence the signal will subsequently be transmitted from Anthorn 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 services that disseminate time to computers via telephone time codes and internet time servers using the NTP protocol. 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 EUROMET 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.

5 Participation in the development of the Galileo Reference Timescale

NPL is performing the 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 [7-10].

In addition NPL is performing a significant role in the development of the Kayser Threde-led Precise Time Facility, which will generate the system time scale for Galileo, including the design and prototyping of the clock, steering and time transfer algorithms and end-to-end testing of the final installed hardware.

6 Optical Frequency Standards

NPL has continued development of optical frequency standards based on narrow transitions in single cold trapped ions. Clock transitions in two systems are under study, namely the 5s $^2S_{1/2}$ – 4d $^2D_{5/2}$ electric quadrupole transition in $^{88}Sr^+$ and the $4f^{14}6s$ $^2S_{1/2}$ – $4f^{13}6s^2$ $^2F_{7/2}$ electric octupole transition in $^{171}Yb^+$. The $^2S_{1/2}$ –$^2D_{5/2}$ 445 THz electric quadrupole transition in $^{88}Sr^+$ has been recommended to the CCTF by the CCL/CCTF JWG as one of three potential optical secondary representations of the second. NPL activity on a neutral atom lattice project is scheduled to start later this year.

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 [1], we measured the frequency of the 674 nm clock transition to be 444 779 044 095 484.6(1.5) Hz, with a fractional uncertainty of 3.4×10^{-15} [4]. Following recent re-appraisal of the Cs fountain uncertainty [2], this value is corrected to 444 779 044 095 484.2 (1.7) Hz. This value is in excellent agreement with earlier, less accurate measurements [11, 12] as well as a more recent measurement from NRC [13]. Further frequency measurements carried out after this change confirm our previous result, although with a three times larger uncertainty because significantly less data was taken and the NPL caesium fountain was only operating for part of the data-taking period. The linewidth of the 674 nm probe laser system during the frequency measurements described above was typically 50–100 Hz and a probe laser pulse duration of 5 ms was 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.

In order to optimize the performance of the $^{88}Sr^+$ optical frequency standard so that its stability is close to the quantum projection noise limit set by the 0.4 s lifetime of the 4d $^2D_{5/2}$ level, the 674 nm probe laser linewidth must be reduced to the sub-Hz level for timescales up to several tens of seconds. Recently, effort has been put into reducing the probe laser linewidth and drift rate, for example by reducing etalon effects in the path between the laser and the ULE cavity (which cause fluctuations in the baseline of the Pound-Drever-Hall error signal) and by reducing phase noise introduced in the beam path to the ion trap. The effect of these improvements has been assessed 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.
The Allan deviation of the beat (without linear drift compensation) was observed to have an optimum frequency stability of about 2.5 parts in 10^{15} at 1 s [14].
To assess whether these probe laser improvements enable narrower clock transition linewidths to be observed, four scans were taken of the $m_j = 1/2 \rightarrow m_{j'} = 1/2$ Zeeman component of the 5s $^2S_{1/2}$ – 4d $^2D_{5/2}$ transition, using frequency steps of 2 Hz and compensating for the linear component of the ULE cavity drift. At each point 40 interrogation cycles were performed with a probe pulse duration of τ = 100 ms.
The line profile is expected to be a convolution of the laser spectrum with the Fourier transform of the τ = 100 ms probe pulse. A fit of the experimental profile to this function yields a value of τ = 107(5) ms, corresponding to a full width at half maximum intensity linewidth of 9 Hz, consistent with the transform limit [14]. This result represents a factor of 20 improvement over our previously observed clock transition linewidths and further reduction can be anticipated in the future.

Finally, a second separate trapped strontium ion frequency standard is under construction, with the intention of evaluating systematic frequency uncertainties on the 674 nm optical clock transition by means of two-trap comparisons

Ytterbium ion octupole clock transition

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 [15, 16]. 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 [17, 18]. Using a femtosecond optical frequency comb the frequency of the 467 nm clock transition has been measured to be 642 121 496 772.3(6) kHz [18]. The major contributions to the uncertainty of this result are the 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. In order to achieve higher measurement accuracy, several improvements to the experimental arrangement are currently underway.

A crucially important parameter in the experiment is the probe laser linewidth. As this is reduced the spectral intensity increases, making it possible to increase the beam diameter at the position of the the trapped ion. This reduces the sensitivity of the ac Stark shift to alignment drifts as well as reducing the total intensity whilst maintaining the same excitation rate. For sub-Hz laser linewidths it is expected that the ac Starkshift will no longer dominate the systematic uncertainty budget. Recently, heterodyne beat measurements have been carried out between light beams whose frequencies are independently stabilized to two ULE cavities. With compensation for the linear component of the ULE cavity drift, beat linewidths of about 5 Hz and 20 Hz are observed for averaging times of 1 s and 100 s respectively. By contrast, the observed spectrum of the 467 nm clock transition exhibits a significantly larger linewidth of around 200 Hz [18]. The origins of this spectral broadening have been traced to trap vibrations. Subsequent improvements to the trap mounting arrangement have resulted in reduction of the heterodyne beat linewidth and experiments are now underway to assess the extent to which corresponding improvements in the clock transition linewidth are observed. Absolute frequency measurements on a reduced linewidth octupole transition are intended, and 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.

References:

[1] K. Szymaniec, W. Chalupczak, P.B. Whibberley, S.N. Lea, D. Henderson, Metrologia **42** (2005) 49.

[2] K. Szymaniec, W. Chalupczak, P.B. Whibberley, S.N. Lea, D. Henderson, Metrologia **43** (2006) L18.

[3] A. Bauch, J. Achkar, S. Bize, D. Calonico, R. Dach, R. Hlavac, L. Lorini, T. Parker, G. Petit, D. Piester, K. Szymaniec, P. Uhrich, Metrologia **43** (2006) 109.

[4] H.S. Margolis, G.P. Barwood, G. Huang, H.A. Klein, S.N. Lea, K. Szymaniec, P.Gill, Science **306** (2004) 1355.

[5] W. Chalupczak, K. Szymaniec, Phys. Rev. A **71** (2005) 053410.

[6] Y.B. Ovchinnikov, Opt. Comm. **249** (2005) 473.

[7] "A Kalman filter clock algorithm for use in the presence of flicker frequency modulation noise", J A Davis, C A Greenhall and P W Stacey, Metrologia 42 (2005) 1-10.

[8] "The development of a Kalman filter clock predictor", J A Davis, C A Greenhall and R Boudjemaa, Proc. 19th European Frequency and Time Forum, pp 90-95, 2005.

[9] "Calibration of Six European TWSTFT Earth Stations Using a Portable Station", D Piester, J Achkar, J Becker, B Blanzano, K Jaldehag, G de Jong, O Koudelka, L Lorini, H Ressler, M Rost, I Sesia, and P Whibberley, Proc. 20th European Frequency and Time Forum, 2006.

[10] "Fidelity – Developing the prototype Galileo Time Service Provider", I.K. Poyner, J A Davis, J Nawrocki, A Bauch, T Levin, J Marechal, P Tavella, P Uhrich and A Vooght, Proc. 20th European Frequency and Time Forum, 2006.

[11] H. S. Margolis, G. Huang, G. P. Barwood, S. N. Lea, H. A. Klein,W. R. C. Rowley, P. Gill, and R. S. Windeler, *Phys. Rev. A* **67**, 032501 (2003).

[12] A. A.Madej, J. E. Bernard, P. Dubé, L.Marmet, and R. S.Windeler, *Phys. Rev. A* **70**, 012507 (2004).

[13] P. Dubé, A. A. Madej, J. E. Bernard, L. Marmet, J.-S. Boulanger, and S. Cundy, *Phys. Rev. Lett.* **95**, 033001 (2005).

[14]. G. P. Barwood, P. Gill, G. Huang, and H. A. Klein, Submitted to *IEEE Trans. Instrum. Meas.* (2006).

[15] M. Roberts, P. Taylor, G. P. Barwood, P. Gill, H. A. Klein, and W. R. C. Rowley, *Phys. Rev. Lett.* **78**, 1876–1879 (1997).

[16] M. Roberts, P. Taylor, G. P. Barwood, W. R. C. Rowley, and P. Gill, *Phys. Rev. A* **62**, 020501(R) (2000).

[17] P. J. Blythe, S. A.Webster, H. S.Margolis, S. N. Lea, G. Huang, S.-K. Choi,W. R. C. Rowley, P. Gill, and R. S. Windeler, *Phys. Rev. A* **67**, 020501(R) (2003).

[18] K. Hosaka, S. A.Webster, P. J. Blythe, A. Stannard, D. Beaton, H. S.Margolis, S. N. Lea, and P. Gill, *IEEE Trans. Instrum. Meas.* **54**, 759–762 (2005).