Report to the 16th session of the Consultative Committee for Time and Frequency (CCTF), 1st - 2nd April 2004

Introduction

This report summarises the activities of the National Physical Laboratory in the generation and dissemination of timescale. 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 brief mention of activity in optical frequency standards.

1 Primary Standard

The NPL primary standard (NPL CSF1) is based on (100) - geometry for the laser beams of a magneto-optical trap (MOT). The atoms are collected in an MOT but launched after the cloud has been allowed to expand to centimetre size. The atoms pass through a pulsed rf travelling wave for state selection. The rf pulse is detuned to control the number of atoms state-selected. The fountain is operated with frequency measurements made at alternate atom numbers (two launches at one number, two at another, etc.). The alternate atom numbers are close to unity (in arbitrary units) and half of that number. In this way, the frequency data is continuously corrected for spin exchange shift.

The fountain frequency is corrected for 2nd order Zeeman, Black Body, Spin-exchange, Gravitational, and Microwave leakage. Microwave leakage produces a shift of 8 E-16. The combined uncertainty with which we measure our laboratory timescale is 1.6 E-15 (fractional frequency at one standard deviation).

We have compared our fountain with PTB CSF1 for 5 days at MJD 52995-53000. The frequency was found to differ by 1.8 E-15, well within the uncertainty of the remote frequency transfer using TWSTFT.

NPL CSF1 was operated for 30 days at MJD 53054-53084 when our uncertainties, including the TWSTFT link were 1.8 E-15.

We have an experimental fountain for investigation of optical lattice cooling. We have cooled atoms to 200 nK in a stationary (laboratory) reference frame and are able to load 90% of the MOT population into the lattice. At present we are optimising the adiabatic transfer of atoms to the m_f=0 state, having achieved approximately 40% transfer.

2 Time Scale

NPL's clock ensemble has been enhanced by the purchase and commissioning of a third active hydrogen maser. The new 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. Monitoring of the offsets between the standards in the clock ensemble has been enhanced greatly by the commissioning of two phase comparators to log the phase differences between the 10 MHz outputs, and new logging systems based on sub-nanosecond resolution counter-timers to measure the offsets between the one-pulse-per-second signals.

Recently there has been a programme of research and development into time scale analysis techniques and associated algorithms. The initial work concentrated on the resolution of noise parameters for power law noise processes found in time and frequency measurements [2]. A spin-off from this work has been the development of a UTC-UTC(NPL) clock predictor that is now routinely used on NPL's clock data. The clock predictor's performance is currently under evaluation. The most recent work has been in the description of Flicker Frequency Modulation (FFM) in terms of a linear combination of Markov processes. An immediate application of this work has been in the development of a Kalman filter based clock algorithm that is designed to perform close to optimally over all averaging times in the presence of FFM [3]. Initial tests of the algorithm have proved very promising. An implementation using real data from NPL's three active hydrogen masers is currently under way. The ultimate aim of the work is to significantly improve the stability of NPL's timescale UTC(NPL).

3 Time Transfer Activities

NPL has enhanced its satellite time transfer hardware and associated links. The hardware includes two two-way time transfer earth stations, two geodetic GPS quality time transfer receivers (Ashtech Z12-T and JAVAD Legacy) and several of its own (TimeTrace) GPS common-view receivers, designed in collaboration with Time and Frequency Solutions. NPL has also maintained an International GPS Service (IGS) station. During this current year work has been underway to enhance the two-way earth stations, and enhance the operation of the geodetic quality GPS receivers.

Time transfer hardware under evaluation has included a JAVAD geodetic quality GPS receiver, a visiting X-band two-way earth station, and NPL's own Timetrace GPS common-view receiver. Currently two Loran C receivers are being evaluated.

There have been studies of time transfer algorithms and analysis techniques. The early work concentrated on resolving noise parameters in measurement data and estimating the Allan variance of unevenly spaced two-way data using a new second difference variance. [4] . Work has been directed to designing a Kalman filter based time transfer combining algorithm, with the aim of optimally combining measurements from several sets of hardware used on a common time transfer link [4]. The algorithm has been tested on simulated data, an implementation using real data still has to be completed.

4 Services

The MSF 60 kHz Standard Time and Frequency Signal, broadcast from the Rugby Radio Station, remains the principal method of disseminating time and frequency within the UK.

NPL's GPS common-view service became operational at the start of 2002 and has been operating continuously since then [6]. This service provides UK users with time and frequency with an uncertainty of better than 20 ns.

NPL continued to operate its telephone time transfer service, clock and GPS Disciplined Oscillator calibration service, and is currently setting up an Internet based time dissemination service based on the use of NTP servers.

NPL is an active participant in the EUROMET time and frequency technical committee, and is involved in the international programme to benchmark and publish the capabilities of its services in the form of CMC tables.

5 Galileo

The European Space Agency (ESA) and the European Commission (EC) are jointly developing a Global Navigation Satellite System, known as Galileo, which is planned to be fully operational from 2008. The UTC reference for Galileo has not yet been decided. Since the last CCTF in 2001 there have been a number of developments related to a future Galileo time service.

In the UK, Booz-Allen-Hamilton carried out a government-funded study into the Galileo Time Interface between November 2001 and May 2002. Booz-Allen-Hamilton consulted with the following stakeholders: NMI's (NPL, PTB, LPTF, VSL and IEN), BIPM, ESA, and Astrium. They then assessed the issue from a number of different angles (technical, legal, commercial, institutional, etc.) to arrive at a preferred solution. The Booz-Allen-Hamilton Report was presented at the IoN GPS 2002 Conference [7].

ESA have funded the development of a Galileo System Test Bed, which includes provision for experiments on a Precise Timing Facility (PTF) to realise an experimental Galileo System Time (E-GST) and for the steering of E-GST to TAI [8]. IEN are taking the leading role here in the NMI community, with PTB and NPL providing data and equipment in support of the GSTB experiments. The version 1 of the GSTB only includes ground infrastructure. Version 2 allows for at least one experimental Galileo satellite by 2006. The UK carried out a small study into GSTB version 2 issues, which was published at the IoN GPS 2002 conference [9].

In the summer of 2003, ESA and the EC issued a number of contracts to consolidate the system design, and to promote other aspects of the Galileo programme such as demonstrations of future Galileo applications. Three contracts were issued related to the Galileo Time Interface, two parallel contracts from ESA to LogicaCMG and Galileo Industries to consolidated the design of the Galileo Mission Segment (which includes the Galileo Primary Timing Facilities), and one contract from the EC to FDC for mission consolidation activities including the definition of the Galileo Time Service Provider (i.e. the link from Galileo to UTC). NPL is working on all three contracts. In particular, the work package for the Galileo Time Service Provider is a joint activity for IEN, PTB and NPL. All three projects conclude in the second half of 2004, with calls for follow activities anticipated in May 2004 for the Time Service Provider (EC Framework Programme 6: 2nd Galileo Call) and late 2004/early 2005 for PTF activities (ESA Galileo Phase C/D/E activities).

It is also worth noting that, during 2003, Galileo accepted a new requirement for the measurement and broadcast of the offset between the Galileo and GPS system times (GGTO). The motive for the broadcast of GGTO information is to assist interoperability of GPS and Galileo in urban environments, where there is a greater risk of receiving signals from only a few GNSS satellites. GGTO developments are being absorbed into studies for other elements of the Galileo timing systems, such as the PTF.

6 Optical Frequency Standards

NPL is developing optical frequency standards [10-12] based on narrow transitions in cooled single ions of $^{88}Sr^{+}$ and $^{171}Yb^{+}$. The strontium ion transition is the electric quadrupole $^{2}S_{1/2} – ^{2}D_{5/2}$ transition at 445 THz (674 nm). The ytterbium ion transition is the ultra-weak electric octupole $^{2}S_{1/2} – ^{2}F_{7/2}$ transition at 642 THz (467 nm). These standards are evaluated against the NPL primary standard using femtosecond comb technology[10].

References

[1] “Initial Evaluation of the NPL Caesium Fountain Frequency Standard”, K. Szymaniec, W. Chalupczak, D. Henderson. Proceedings of the joint Frequency Control Symposium and European Frequency and Time Forum, May 2003, Tampa, Florida.

[2] “Least-squares analysis of time series data and its application to two-way satellite time and frequency transfer measurements”, P M Harris, J A Davis, M G Cox and S L Shemar, Metrologia **40**, 2003, S342-S347.

[3] “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. Proceedings of the 35th Precise Time and Time Interval meeting, San Diego, California, 2003.

[4] “The characterization of regular but unevenly spaced TWSTFT data using second-difference statistics”, J A Davis, P M Harris, S L Shemar and M G Cox, Metrologia **40**, 2003, S312-S318.

[5] "Combining time transfer measurements using a Kalman filter", J A Davis, P W Stacey, P M Harris, M G Cox. Proceedings of the 34th Precise Time and Time Interval meeting, Reston Virginia,Dec 2002, pp 53-68.

[6] "Commissioning and validation of a GPS common-view time transfer service at NPL" J A Davis, M. Stevens, P.B. Whibberley, P.W.Stacey and R Hlavac . Proceedings of the joint Frequency Control Symposium and European Frequency and Time Forum, May 2003, Tampa, Florida.

[7] "The Galileo Time Interface - Disseminating UTC to Users", Sally Basker and John Laverty, Proceedings of the IoN GPS 2002 Conference, 2002

[8] "The Galileo System Test Bed for early prototyping and experimentation of Galileo algorithms", Marco Falcone, Francisco Amarillo-Fernandez, Joerg Hahn, and Hugues Favin-Leveque. Proceedings of the IoN GPS 2002 Conference, 2002.

[9] "A Novel, Low-Cost Galileo Demonstrator", S Basker, A Sage, P Norris, S Martin, J Laverty, J Davis, A Batchelor, E Stansfield, T Moore, C Hill, and J Owen Proceedings of the IoN GPS 2003 Conference, 2003.

[10] Margolis HS et al., Phys Rev A **67**, 032501 (2003)

[11] Blythe PJ, Webster SA, Hosaka K and Gill P, J Phys B: At. Mol. Opt. Phys. **36** 981(2003)

[12] P Gill, GP Barwood, G Huang, HA Klein, PJ Blythe, K Hosaka, RC Thompson, SA Webster, SN Lea and HS Margolis, Physica Scripta Topical Series, 2004 to be published.