TIME AND FREQUENCY ACTIVITIES AT THE NATIONAL PHYSICAL LABORATORY

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Abstract

The Time and Frequency group at the National Physical Laboratory (NPL) maintains an active program of work in time and frequency metrology. This paper provides an overview of the group's principal activities. These include the maintenance and development of the national time scale UTC (NPL), development of a cesium fountain primary frequency standard and research into cold-atom standards and techniques, time transfer activities, development of data analysis methods and clock algorithms, knowledge transfer activities, and the operation of services for time and frequency dissemination in the UK.

INTRODUCTION

The National Physical Laboratory (NPL) is the national metrology institute for the UK. The Time and Frequency group at the NPL maintains the UK national time scale UTC (NPL), disseminates time and frequency in the UK, and contributes to the formation of TAI and UTC. The group also undertakes research to maintain a leading position in the international time and frequency community, and acts as a focus for time and frequency-related issues. During the past few years, the activities carried out by the Time and Frequency group have been evolving to provide a stronger focus on key activities that underpin the group's primary role – that of the maintenance and development of UTC (NPL). In particular, greater effort is being put into the development of improved methods for analyzing time-related data sets, and into improved cold-atom microwave frequency standards.

TIME SCALE ACTIVITIES

THE UK NATIONAL TIME SCALE UTC (NPL)

The core role of the group is the maintenance of an ensemble of atomic frequency standards from which the national time scale UTC (NPL) is generated. The present clock ensemble consists of three Datum (formerly Sigma-Tau) active hydrogen masers and three Agilent (formerly Hewlett-Packard) cesium clocks (two are high performance and one standard performance). At present, the standard frequency output from one of the masers is used to generate the time scale UTC (NPL), and this maser provides the reference against which the other standards are compared. Frequency corrections are applied to the maser's frequency synthesizer only when required to keep UTC (NPL) within around 30 ns of UTC, typically every 6-8 months. The third active hydrogen maser was delivered to NPL in January 2002 and was installed in the new NPL building. A pair of 1000 m cables was installed across the NPL site to link the new maser with the existing clock ensemble and, once fully characterized, will enable maser three to be fully integrated into the time scale. A GPS common-view link between the two locations will shortly be established.

SATELLITE TIME AND FREQUENCY TRANSFER

UTC (NPL) is routinely compared against other primary time scales using a variety of satellite time transfer methods. Both C/A and P3 code GPS common-view time transfer are carried out, using Time & Frequency Solutions TimeTrace multi-channel C/A code receivers and an Ashtech Z12T geodetic-quality GPS receiver respectively. NPL has recently participated in a BIPM-led study into the use of P3 data that showed advantages over the use of single-channel data for long-baseline GPS common-view links.

NPL operates an International GPS Service (IGS) station identified as NPLD. This is based on an Ashtech Z12T GPS receiver and is fully automated. RINEX data obtained from the NPLD station are also used by the Astronomical Institute of the University of Berne to calculate precise geodetic-quality time transfer measurements between NPL and other UTC (k) laboratories. A Javad Legacy geodetic quality GNSS receiver with GPS, GLONASS, and SBAS capabilities was purchased recently. Work is underway to commission the receiver and to perform direct comparisons against measurements made using the Ashtech Z12T receiver. It is intended to use the Javad receiver to monitor the timing performance of EGNOS signals.

NPL has participated in Two-Way Satellite Time and Frequency Transfer (TWSTFT) measurement sessions since 1993. Today, the group continues to carry out both European and transatlantic sessions. These are performed three times per week, although work is well advanced to move to daily sessions. Two earth stations are available, and work is being completed to allow fully automated and independent operation of the two stations that will allow participation in daily sessions. Data from both TWSTFT and GPS common-view measurements are contributed to the BIPM for use in the calculation of TAI.

A portable clock trip to VSL, the Netherlands, was carried out in May 2002 to calibrate the NPL-VSL and NPL-PTB time transfer links. During 2001, NPL was loaned a portable X-band TWSTFT earth station from USNO. This station was used both to calibrate independently the TWSTFT earth stations at NPL and to make direct comparisons between the performance of a Ku-band and an X-band TWSTFT link.

NPL regularly takes part in time-transfer calibration campaigns, most of which have been carried out using GPS common-view receivers. NPL also intends to take part in the 2003 TWSTFT campaigns that will be performed using small portable TWSTFT earth stations.

RESEARCH INTO DATA ANALYSIS METHODS

The NPL Time and Frequency group has carried out studies into the identification of noise processes present in time and frequency data **[1]**. The results of this work are being applied to the development of a clock predictor for (UTC - UTC (NPL)). Work has started on developing an algorithm that will combine measurements from all of NPL's atomic clocks to produce a composite free-running time scale. A second steering algorithm is being considered to steer the free-running time scale to UTC. The aim is to implement a hardware-based time scale controlled by a steering algorithm that will be both more stable and more reliable than a time scale based on a single maser.

Another study has addressed the problem of unevenly spaced two-way time transfer data by utilizing a new second-difference variance **[2]**. A Kalman filter-based algorithm for combining data from different time transfer methods (particularly between TWSTFT, geodetic GPS time transfer and GPS common-view time transfer) has also been investigated **[3]**. It is intended to implement this type of algorithm on NPL's key time transfer links with other UTC (k) laboratories.

DEVELOPMENT OF A CESIUM FOUNTAIN PRIMARY FREQUENCY STANDARD

A cesium fountain primary frequency standard **[4]** has been constructed at NPL, building on several years of experience gained through developing and operating an experimental cesium fountain. The fountain primary standard has been operated routinely over many months, and the causes and magnitudes of the frequency shifts present are being studied. It is anticipated that the evaluation of the uncertainty budget will be completed during 2003.

The fountain is configured with the trapping and cooling region in the center, between the C-field chamber and the detection region. The C-field chamber containing the TE_{011} microwave cavity is machined from aluminum, and is enclosed within three layers of mu-metal magnetic screens. The three counter-propagating pairs of cooling laser beams are arranged in an xyz geometry. They are generated by slave lasers injection-locked to light from an extended cavity master laser. An additional extended cavity laser provides repumping light. Polarization-maintaining fibers give spatial filtering of the beams, as well as decoupling the alignment of the frequency control optics from that of the optics around the vacuum chamber. Following the double pass through the microwave cavity, the relative populations of both ground state levels are detected by optical pumping and fluorescence detection. The sequencing of the repeated fountain cycle is under computer control, allowing the operating parameters to be easily adjusted.

Because of the pulsed operation of the fountain, the source of microwaves at 9.192 GHz must have low phase noise, particularly close-to-carrier noise in the range of 0.1 to 100 Hz offset. The scheme adopted uses a dielectric resonant oscillator phase-locked in an offset scheme using a sampling down-converter and a synthesizer with millihertz resolution. The sampling down-converter is driven by a 200 MHz source derived from a pair of phase-locked low noise crystal oscillators, at 5 and 100 MHz. The 5 MHz crystal is in turn loosely phase-locked at 100 MHz to the local time scale frequency reference, an active hydrogen maser.

OTHER FREQUENCY-RELATED ACTIVITIES AT NPL

A range of other research projects are being carried out at NPL in support of the Time and Length metrology programs. The cesium fountain primary standard development is supported by a project to investigate improved cooling techniques and methods of stabilizing the cold-atom density. Another project is aimed at developing a cryogenic ultra-low phase noise sapphire oscillator for the cesium fountain and other microwave frequency standards.

Other teams at NPL are working on the development of ion-trap optical frequency standards based on ytterbium and strontium ions. Activities aimed at the development of the next generation of frequency standards include studies of a cold single ytterbium ion optical frequency standard, and the use of high-stability lasers as optical flywheel oscillators.

TIME AND FREQUENCY SERVICES

SATELLITE TIME AND FREQUENCY DISSEMINATION

Common-view GPS time transfer has long been used to intercompare atomic clocks at primary timing laboratories. NPL now operates a service that utilizes the GPS common-view method to provide customers in the UK and western Europe with high-accuracy time and frequency transfer that is traceable to UTC (NPL) **[5]**. The service normally utilizes the inexpensive TimeTrace GPS common-view receiver developed by the UK company Time & Frequency Solutions in partnership with NPL, together with software produced by NPL. A receiver is located at the customer's site, using the customer's standard as its reference, and GPS data files are transferred to NPL daily via the Internet for processing. Weekly reports are sent to the customer by e-mail.

NPL performs continuous monitoring of the GPS satellite system, viewed from its Teddington site. The measurements are published as daily values for (UTC (NPL) - GPS Time) for UK time and frequency users, and also assist in validating the integrity of the GPS signals when received at GPSDO installations traceable to UTC.

TERRESTRIAL TIME AND FREQUENCY DISSEMINATION IN THE UK

The MSF 60 kHz transmission is the principal method of time and frequency dissemination in the UK and is widely used to synchronize inexpensive radio-controlled clocks. The MSF signal is broadcast from the Rugby Radio Station by British Telecom plc under contract to NPL. It provides complete coverage of the UK and may be received over much of Europe. The phase of the 60 kHz carrier is monitored at NPL and daily values for the cumulative offset from UTC (NPL) are published in a monthly bulletin to provide frequency traceability with an uncertainty of $3 \cdot 10^{-12}$ for an averaging time of 1 day.

A 198 kHz signal broadcast from Droitwich in the UK is also monitored at NPL and its daily phase offset from UTC (NPL) published in the monthly bulletin so that this signal can also be used (in England and Wales only) as a traceable frequency reference.

NPL operates a modem-based telephone time service, allowing a user with appropriate software to access a time code traceable to UTC (NPL) and set the clock of a PC to the correct time. It is intended to offer a public NTP (Network Time Protocol) service to disseminate time via the Internet during 2003, and NTP servers have been installed. NPL is able to carry out a range of other time and frequency-related measurements on request, including the calibration of GPS-disciplined oscillators and frequency standards, both at NPL and off-site using a portable cesium clock.

KNOWLEDGE TRANSFER ACTIVITIES

An important aspect of NPL's work is to support UK businesses by providing technical advice through a range of knowledge transfer activities. Information for users of NPL's time and frequency services is provided in the Time pages of the NPL Web site, which are updated regularly. NPL also operates an advice service that receives many hundreds of time and frequency-related inquiries each year by e-mail, telephone, and fax from both companies and the general public.

A training course on the use of GPS to obtain traceable time and frequency was run at NPL in October 2001, and this course will be offered again in 2003.

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