Time and Frequency Activities at the National Measurement Institute, Australia

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***Abstract*—The Time and Frequency group of the National Measurement Institute, Australia, (NMIA) maintains the Australian national standards for time of day and for frequency. Research and development activities of the group include: development of microwave frequency standards in the 10^{-15} accuracy range based on trapped Yb^+ ions; development of GPS common-view time transfer systems, and the use of these systems to deliver traceable time and frequency to a client's premises by continuous remote calibration; two-way satellite time and frequency transfer; and time and frequency dissemination around Australia by means including the recently developed NMIA 'speaking clock' telephone service.**

I. Introduction

On 1 July 2004, three Australian institutions joined together to form a new National Measurement Institute (NMIA): the National Measurement Laboratory, formerly part of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and responsible for maintaining physical measurement standards; the Australian Government Analytical Laboratories, responsible for standards in chemistry and biology; and the National Standards Commission, the body formerly responsible for legal metrology. All of these measurement-related functions are now responsibilities of the new NMIA.

The NMIA inherits the statutory responsibility under Australia's *National Measurement Act (1960)* to maintain standards of physical measurement. This specifically includes the responsibility to maintain Australia's realisation of Coordinated Universal Time, denoted UTC(AUS). The Time and Frequency group within the NMIA maintains and disseminates UTC(AUS), and undertakes a wide variety of research activities to support and develop measurement infrastructure both nationally and internationally.

II. Trapped Yb^+ Ion Frequency Standard

A microwave frequency standard based on the 12.6 GHz ground state hyperfine transition of trapped and laser-cooled $^{171}Yb^+$ ions has been under development at NMIA for many years [1] and [2]. The current uncertainty budget gives an absolute frequency uncertainty projected to be 4 parts in 10^{15} or below, and work is in progress to demonstrate this level of performance. Recent progress has included the design and commissioning of a non-magnetic ultra-high vacuum (UHV) chamber, and preliminary investigations of trap loading by photoionization.

A. Non-magnetic UHV chamber

In the most recent absolute frequency measurement [1], the dominant systematic uncertainty was due to inhomogeneity of the magnetic field across the cloud of trapped ions, which causes a variation in the correction for the quadratic Zeeman shift. The uncertainty in this correction was approximately 5×10^{-14} for this measurement. The inhomogeneity was largely due to the stainless-steel vacuum chamber itself, so that the only way to improve the magnetic environment significantly was to develop a new vacuum chamber made entirely from non-magnetic materials.

The novel alloy CrCu was selected for the vacuum chamber because it is non-magnetic (susceptibility μ–$1\sim10^{-5}$, from measurements made at NMIA) and compatible with UHV: a pre-bake *in vacuo* promotes diffusion of Cr to the material surface, which when oxidized forms a good barrier to interstitial hydrogen and reduces outgassing [3]. The material is hard enough that the conventional ConFlat flange design can be used with metal gasket seals. Large-area viewports for fluorescence collection and high-quality fused-silica windows for laser access are also required; custom glass-to-metal seal solutions for these components were developed with the manufacturer [4].

The new chamber was commissioned in mid-2004, and has a base pressure below 10^{-10} Torr with the current pumping configuration. The homogeneity of the magnetic field, as measured by the width of the field-sensitive $F=0 \rightarrow F=1$, $M_F=1$ hyperfine component of the 12.6 GHz reference transition, has been improved by almost two orders of magnitude. The corresponding uncertainty in the quadratic

Zeeman shift correction has been reduced by the same factor, to below 1 part in 10^{15}.

B. Photoionization

Preliminary investigations of loading the trap using photoionization [5], rather than electron impact ionization, have also been made. Light is required at 399 nm (the resonance transition ${}^1S_0 \rightarrow {}^1P_1$ of the neutral Yb atom), and at any wavelength shorter than 394 nm to promote an Yb atom from the ${}^1P_1$ excited state to above the ionization threshold. Light for the second excitation stage can in principle be provided by a UV LED. The two principal advantages of this technique are that DC fields from stray charge are greatly reduced, and that it eliminates the need for isotopically-enriched ^{171}Yb. Using a frequency-doubled Ti:sapphire laser to generate 399 nm, we have demonstrated both loading of a Yb^+ ion cloud by photoionization and selective loading of a single Yb isotope using a collimated oven.

III. GPS COMMON-VIEW TIME TRANSFER SYSTEMS

The NMIA has developed a GPSCV time and frequency transfer system that is in wide use in the Asia-Pacific region, in particular by a number of national measurement institutes and Australian calibration laboratories. The system typically consists of a PC, custom software, and a GPS receiver, but may also include a frequency standard and other timing hardware. Software developed at NMIA uses raw data logged from the GPS receiver to generate strict CGGTTS-format data [6] for common-view GPS time transfer. The system normally runs completely automatically but can be remotely operated and maintained by NMIA staff via a modem or network connection.

A. Remote calibration

From the point of view of a national measurement institute, a time-transfer system provides the means to deliver traceable time and frequency into a remote location, or equivalently to provide continuous remote calibration of a frequency standard on a client's premises. NMIA has expended significant effort to automate all stages of this remote calibration process, including retrieval of CGGTTS-format data from remote sites, processing to compare remote standards to UTC(AUS) in time and in frequency, and generation and dissemination of reports with the results. NMIA currently provides such a remote calibration service for a number of client laboratories in Australia and the South Pacific.

Furthermore, if staff in the client calibration laboratory connect a device under test (DUT) to the remote frequency standard, it is also possible to control a complete calibration of the DUT from NMIA. This level of remote calibration is effectively at one further remove from NMIA, but can nevertheless be conducted and controlled by remote access to the time-transfer system PC at the client laboratory. Development and verification of methods for this kind of calibration are currently in progress.

B. IGS node

A geodetic monitoring station has been constructed at NMIA Lindfield, in a joint project with Australia's national mapping agency Geoscience Australia (GA). The station is based on a variant of the NMIA-developed time-transfer system, and incorporates a Javad/Topcon Euro-160 dual-frequency geodetic GPS receiver. The station provides a stable antenna mount and good reception to support high-quality GPSCV time transfer. The station contributes data to the Australian Regional GPS Network (ARGN) for mapping and geodesy, and also forms the SYDN node of the International GNSS Service (IGS) network, one of the few such stations co-located with a national timing laboratory.

The same raw GPS data is post-processed to produce both CCTF-format time-transfer data (daily) and RINEX-format geodetic data (daily and hourly), in both cases by software developed at NMIA. RINEX files are automatically uploaded to GA, who co-ordinate all ARGN data. Planned extensions include more rapid and potentially real-time upload of observations, and monitoring and reporting of meteorological data.

A new station co-located with the Parkes radio telescope in New South Wales, Australia, has recently been commissioned in a collaboration between the Australia Telescope National Facility, Geoscience Australia and NMIA. The Parkes radio telescope undertakes extensive observations of millisecond pulsars. Accurate geodesy helps constrain uncertainties arising from earth orientation, and high-precision time transfer links pulsar timescales to TAI. This station has provided the opportunity to extend NMIA software to allow processing of observations from the GLONASS system of satellites. Data from Parkes, referenced to the station maser, should also assist with evaluating and optimising the performance of a new carrier phase time and frequency transfer link between Perth and Sydney (section IV).

C. APMP intercomparison

The Telecommunications Laboratories (TL) in Taiwan commissioned NMIA to build a portable time-transfer system to support round-robin intercomparisons of GPS receiver internal delays among laboratories of the Asia-Pacific Metrology Programme (APMP). Previous APMP comparison campaigns have suffered from poor reliability of a commercial traveling receiver, so high reliability was therefore one of the key design goals for the NMIA portable system.

The comparison campaign, begun in 2004, will visit fifteen laboratories in thirteen countries by the end of 2005. The portable system receiver has also been compared to the calibrated receiver at BNM-SYRTE in Paris, which has acted as the reference point for a number of BIPM campaigns, and to a similar calibrated receiver at NIST in Boulder. It is hoped that the portable time-transfer system will support ongoing intercomparison, important not only for calibrating time-transfer within the region but also to establish the long-term stability of receiver delays.

IV. TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER

NMIA has actively participated in two-way satellite time and frequency transfer (TWSTFT) research in the Asia-Pacific region for many years. A long-running Ku-band link to the National Institute of Information and Communications Technology (NICT) in Japan has now been upgraded to use the new multi-channel time-transfer modem developed by NICT. The Telecommunications Laboratories in Taiwan and NMIA also performed bi-weekly TWSTT sessions via the same satellite (PanAmSat PAS-8) for several years, using satellite time generously made available by NICT.

A C-band TWSTT link was also trialled between TL and NMIA as part of a three-way comparison involving NIST in the United States, beginning in September 2002 and ending in April 2003. Fluctuations in ionospheric delay are much more significant at C-band than at Ku-band owing to the lower frequencies. An attempt to mitigate these ionospheric fluctuations in post-processing was partially successful, using delay corrections calculated from dual-frequency GPS data recorded by receivers collocated with the ground stations. However, notwithstanding these results, time transfer performance will likely always be better at Ku-band where these corrections are so much smaller.

The Frequency Standards and Metrology Group at the University of Western Australia (UWA) is well-known for its development of ultra-stable cryogenic oscillators. Clock ensembles at UWA and NMIA are to be compared for the first time by new TWSTFT and GPS carrier-phase time transfer links, currently being commissioned. The comparison between the two methods should provide important verification of performance, and allow optimisation of link parameters and data processing.

The UWA-NMIA links are being established in preparation for participation in the Atomic Clock Ensemble in Space (ACES) mission, where a high-accuracy cesium beam frequency standard and a hydrogen maser will be flown aboard the International Space Station. High-precision time-transfer to ground stations will enable a variety of fundamental physics tests as well as making a major contribution to international timekeeping. UWA and NMIA form the only ACES User Group in the southern hemisphere.

V. TIME AND FREQUENCY DISSEMINATION

A. *NTP server network*

NMIA operates a number of public stratum 1 NTP (Network Time Protocol) servers, distributed around Australia to minimise network delays in disseminating UTC(AUS) and to provide redundancy in the event of a network or server failure. Each of the remote servers has a local atomic clock which is linked back to UTC(AUS) using one of the NMIA-developed GPS common-view time transfer systems. Custom hardware and software allows us to measure the PC system time with respect to the local reference to better than 10 μs, so that there is an unambiguous record of the NTP server's operation (Fig. 1).

For a number of years, the NTP service was operated with open access. Late in 2002, it became evident that the NTP servers were being flooded with exponentially increasing traffic from many instances of a particular NTP client. Most of this traffic was from the US and was characterized by a distinctive polling pattern.

The client was identified as a small router intended for home use. NTP server addresses had been hard-coded into its firmware, with no way for the owner to change them, and the router continued to send requests indefinitely even if unanswered. The manufacturer agreed to modify the firmware of their devices when contact was finally made.

It seemed likely that this problem would occur again. In view of NMIA's potential liability for network charges, it was decided with regret to close access to the NTP servers in February, 2003. The servers can now only be used by prior arrangement. Potential users must supply the addresses of their NTP client computers, and unauthorised NTP requests are not answered by the servers. Two years later, there are approximately 300 registered users, comprising of large companies, educational institutions, small businesses and individuals. There is about one new connection request per week and an occasional request to change access details. The authorisation process is largely automated so that it typically takes only a few minutes to add a new user.

Although closing access has drastically reduced direct traffic to our NTP servers, the servers are now being used in the way that the architects of NTP intended: namely, users are setting up their own stratum 2 NTP servers, referencing these to NMIA's, and using them in turn to distribute time to their own networks which may include thousands of hosts.

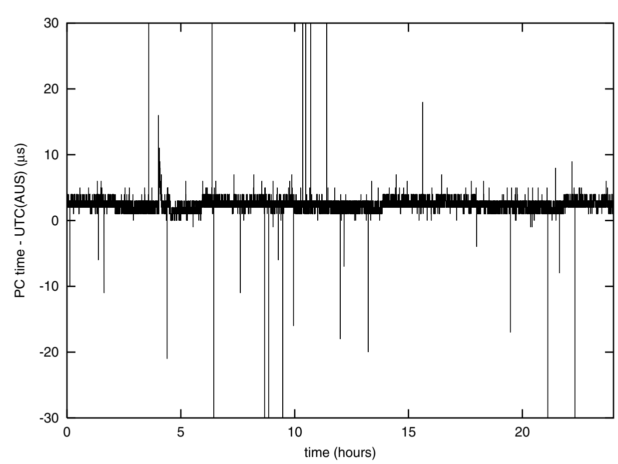

Figure 1. Difference between the PC system time and UTC(AUS), measured over 24 hours on one of the NMIA NTP servers.

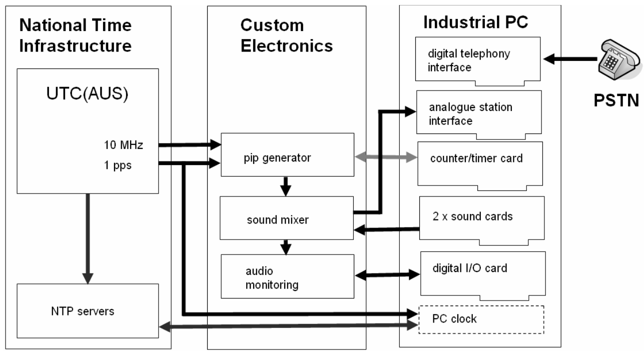

Figure 2. Architecture of the NMIA speaking clock.

B. *Speaking clock*

NMIA has recently completed construction of a speaking clock system (Fig. 2). The system consists of two components: a PC-based digital telephony interface, and purpose-built hardware to generate marker tones from an external reference. At NMIA the tones are references to the clock which realizes UTC(AUS): the tone frequency is synthesized from the 10 MHz output, and the tone timing is directly obtained from the 1 pulse-per-second output. Voice announcements are generated by two sound cards in the PC and combined externally with the marker tones. Complete traceability of the timing information is thus obtained, at the point of injection into the public telephone system.

The speaking clock has eight channels, with one announcement for each of the seven Australian states and territories plus a UTC announcement. Australia nominally has three time zones, but variations in adherence to daylight saving (summer time) mean that each state needs a separate announcement. Rather than providing a separate telephone number for each state, the NMIA speaking clock asks callers to select the desired time announcement from a menu.

Changeovers for daylight saving and leap seconds are automatically handled by the speaking clock software. The digital telephony interface can presently handle thirty simultaneous calls; this can be easily expanded and so is suitable as a platform for a national service. Since the system is PC-based, it can also be readily customized, for example to provide announcements in multiple languages.

VI. SUMMARY

The formation of the new NMI offers great opportunities for closer collaboration among related areas of research and development, and establishes a single point of contact providing services across all areas of metrology to government, industry and the community. NMIA's continuing challenge is to use its technical expertise in measurement to foster innovation in the Australian economy, provide training both nationally and internationally, and collaborate effectively with colleagues in the Asia-Pacific region and around the world.

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