TIME AND FREQUENCY METROLOGY IN AUSTRALIA: THE ROLE OF THE CSIRO NATIONAL MEASUREMENT LABORATORY

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Abstract

Time and frequency metrology has changed dramatically in the last 10 years, with the introduction of Global Positioning System technology into timekeeping and, more recently, the introduction of Universal Coordinated Time (UTC) into the Australian National Measurement Act. This paper outlines the technical aspects of time and frequency traceability in Australia, and how NML discharges its responsibilities in this area.

1. INTRODUCTION

The National Measurement Act requires CSIRO to maintain, or cause to be maintained, Australia's standards for measurement of physical quantities. The CSIRO National Measurement Laboratory (NML) discharges CSIRO's responsibilities under the Act.

Until mid 1997, the National Measurement Act explicitly deemed the time of day not to be a physical quantity, so that NML's responsibility in the Time and Frequency area has been limited to the maintenance and dissemination of standards for frequency and time interval. The reference for time of day, known as Australia's realisation of Universal Coordinated Time, or UTC(Aus), is presently maintained by the Australian Surveying and Land Information Group (AUSLIG) under contract to the National Standards Commission.

In June 1997, legislation which amends the National Measurement Act to remove the exclusion of time of day as a physical quantity, and to include Universal Coordinated Time (UTC) as the reference time scale for the time of day in Australia, was passed by both houses of Federal Parliament. The amended Act provides a common legal time reference for all matters, technical and otherwise, in which the precise time of occurrence is an issue, and implicitly places responsibility for UTC(Aus) on NML.

The inclusion of UTC(Aus) in the National Measurement Act places additional responsibility on NML to ensure that the technical aspects of the legal traceability of time are sufficiently well understood, and demonstrated, to allow end-users to obtain formal accreditation (through NATA, for example) for the realisation of time of day with a known uncertainty, using equipment which suits their purposes and their budget.

The purpose of this paper is:

- To introduce some of the technical aspects and concepts of modern time and frequency metrology.
- To survey the present system by which time and frequency are disseminated in a legally traceable manner in Australia.
- To outline the present and future role of NML in this area

2. TIME AND FREQUENCY METROLOGY: AN INTRODUCTION

A discussion of high accuracy time and frequency dissemination necessarily invokes a number of technical concepts, and, inevitably, many acronyms. Consequently, many of the concepts and techniques mentioned are briefly explained in the appendix. A concept or acronym which is explained in the appendix is underlined at its first mention in the main text.

Time and frequency are very closely related quantities. All man-made clocks, from the simplest to the most sophisticated and accurate, record the passage of time in terms of the rate, or frequency, of occurrence of some event; for example, the passage of grains of sand through an hourglass, the swinging of a pendulum, the vibrations of a quartz crystal (as in a quartz wristwatch) or the oscillations of an atomic nucleus (as in an atomic clock).

Consider, for example, a modern bedside alarm clock. This clock probably uses a quartz crystal oscillating electrically 32768 times per second as its *frequency reference*, and updates its digital display by one second, or advances its second hand, each time its internal circuitry counts 32768 oscillations of the crystal. The user of such a clock typically wants to know two things: is it set to the correct time, and does it run fast or slow - that is, how often does it need to be reset? The clock can be set to the correct time in a number of ways, for example, using signals from the Telstra 'speaking clock', which are derived from the Telstra master clock, which is maintained to within a known tolerance of <u>UTC</u>. By so doing, the user has synchronised the clock with the Telstra master clock, and thus has carried out a *time transfer* operation. The question as to whether the clock is fast or slow is resolved by comparing its reading with the speaking clock at a later time. This comparison determines whether its frequency reference is adjusted to the correct frequency, so that two or more time transfer operations constitute a *frequency transfer*.

In this way it is easy to set the alarm clock with an accuracy of better than one second, and the purpose for which this clock is intended is very well served by these time transfer techniques. However, if a user was setting a more sophisticated clock intended to display the time with sub-millisecond accuracy (for example, to time-stamp computer transactions), then it would be essential to consider the delay due to the passage of the time signals from the Telstra master clock through the telephone lines. Quantifying this *propagation delay* is the most difficult problem in accurate time transfer. The delay does not necessarily affect frequency transfer, since as long as the delay is known not to change it is still possible to determine if the clock is running fast or slow, even though it may not be reading the correct time.

Several methods of time transfer are presently in use in Australia, including a dedicated radio station (radio VNG, operated by the National Standards Commission), Telstra landlines, common-view of domestic communications satellites and signals from the Global Positioning System (GPS) satellite constellation. These techniques generally involve the user receiving signals locally, and referring to a computer bulletin board or a report issued by a timing laboratory, listing offsets and corrections to be applied.

Each system is presently useable for legally traceable frequency transfer, however, only the GPS system is presently capable of Australia-wide legally traceable *time* transfer with accuracies better than a few milliseconds, and then only with expensive equipment (approximately $20,000 for a suitable receiver). It is, however, likely that with suitable monitoring, the upper and lower limits on the propagation delays of less expensive time transfer techniques can be determined, and the time uncertainty of these techniques can consequently be significantly improved. In particular, with appropriate monitoring of the GPS system within Australia, it will almost certainly be possible to use low cost (less than $1000) navigation receivers for legally traceable time transfer at the sub-millisecond level. These receivers have recently been approved by NATA for use in traceable frequency transfer, and their performance and integrity for use in time transfer are currently being investigated.

3. TIME AND FREQUENCY DISSEMINATION WITHIN AUSTRALIA: THE PRESENT SYSTEM

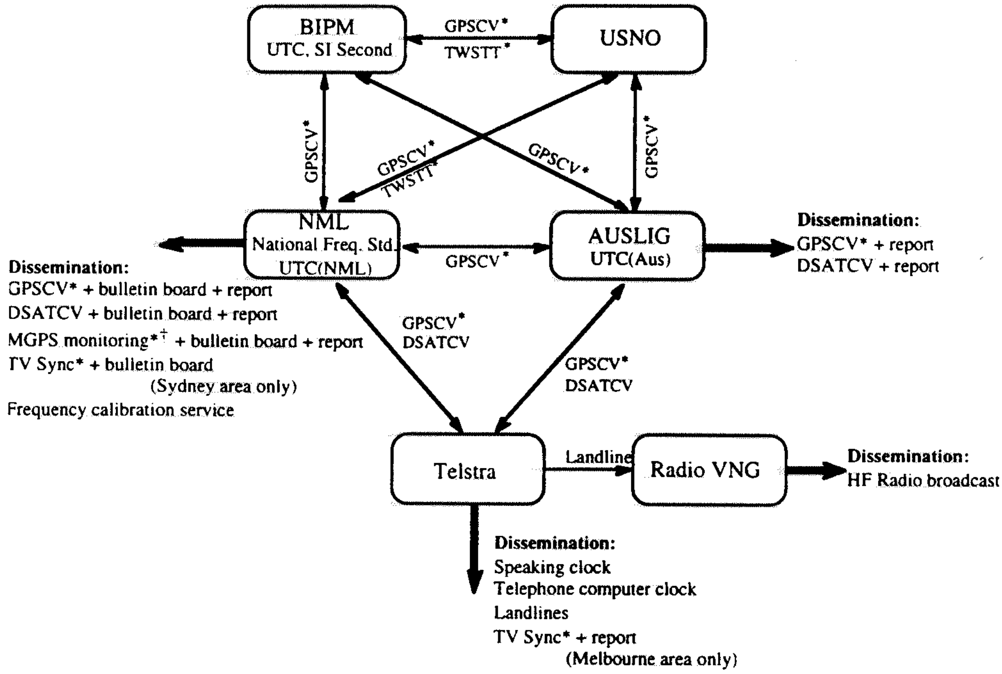
The system for dissemination of precise time and frequency within Australia is shown, from a technical point of view, in figure 1. Traceability of Australian time and frequency to the basic unit of time interval, the Système Internationale (SI or metric) second, is maintained by continuous international time transfer by NML in Sydney, and the AUSLIG Orroral observatory 60 km south of Canberra. The SI second is realised at NML with an uncertainty smaller than 2 parts in 10^{13}. UTC is realised at AUSLIG and at NML with an accuracy of better than 200 ns, and is likely to improve substantially with the planned commissioning of a Two-Way Satellite Time Transfer (TWSTT) link between NML and the United States Naval Observatory (USNO).

Both NML and AUSLIG maintain 1 pulse per second timing outputs within ± 1 μs of UTC, the AUSLIG output being designated UTC(Aus), the official Australian realisation of UTC.

Dissemination of time traceable to UTC(Aus) and hence UTC throughout Australia has to-date been provided principally by Telstra, via the speaking clock and landline services. Traceability of the Telstra time and frequency signals to the SI second and UTC(Aus) is presently maintained by GPS common view and domestic satellite common view links with AUSLIG and NML.

The Australian standard for frequency and time interval, the National Frequency Standard (a caesium atomic clock), is maintained by NML. Precise frequency and time interval are disseminated by NML by several methods, to suit the requirements and budgets of users. AUSLIG and Telstra both hold delegations from NML for legally traceable frequency and time interval dissemination. The techniques for legally traceable frequency and time interval dissemination currently in use are compared on a number of criteria in table 1.

The present dissemination system is still far from ideal, since, for example, there is still no method other than shipping a frequency standard to a calibration laboratory in Sydney or Melbourne, for



Abbreviations

GPSCV	Global Positioning System Common View
MGPS	Multichannel Global Positioning System
DSATCV	Domestic Satellite Common View
TV Sync	Television Synchronation pulse
TWSTT	Two-Way Satellite Time Transfer (to be commissioned in 1997)
UTC	Universal Coordinated Time
UTC(AUS)	Australia's realization of UTC: A clock maintained within ±1μs of UTC
UTC(NML)	NML's realization of UTC: A clock maintained within ±1μs of UTC

* Denotes techniques suitable for sub-millisecond accuracy time transfer
† Available January 1997 for frequency transfer

Figure 1: The present system for dissemination of precise time and frequency within Australia.

the dissemination of legally traceable frequency to Perth or Adelaide at accuracy levels better than 1 part in 10^8 (for which there is demand). Until recently there was no suitable technology to satisfy this requirement at reasonable cost, and the problem is presently being addressed by NML's introduction of the multichannel GPS (MGPS) technique for frequency transfer (now available for use in most areas of the eastern states).

Australia's contribution to UTC

Australia contributes to UTC by reporting GPS common-view (GPSCV) time transfer data from (currently) two clocks at AUSLIG, three clocks at NML, one clock at the Tidbinbilla tracking station near Canberra and one clock at the Hewlett-Packard laboratories in Melbourne. Reporting of clock data to BIPM is essential for maintaining international traceability of Australian time and frequency.

4. TECHNICAL CONSEQUENCES OF THE INCLUSION OF UTC(AUS) INTO THE NATIONAL MEASUREMENT ACT

The appearance of UTC(Aus) in the National Measurement Act places a clear responsibility on the measurement standards infrastructure to disseminate this time scale in a manner which satisfies the various requirements of users. Of all the time and frequency transfer techniques presently in use within Australia (table 1), only GPS common view and the very recently introduced multichannel GPS technique are considered to have demonstrated sufficient integrity to be used for legally traceable time transfers at the sub-millisecond level. However, the GPS common view technique is too expensive for most users, and the use of the multichannel GPS technique in areas of Australia other than the Sydney-Canberra-Melbourne area is not feasible until relatively simple and automated systems to monitor GPS time in other regions of Australia are developed and installed by NML.

Method	*Accuracy (Time) (single reading)*	*Accuracy (Freq) (1 day average)*	*Receiver cost (Approx)*	*Present coverage*	*Future coverage*
GPS Common View (GPSCV)	< ± 100 ns	< 1 part in 10^{12}	$20k	Australia-wide	Australia-wide
Multichannel GPS (MGPS) Note 1	< ± 1 μs	< 1 part in 10^{11}	$2k	Eastern Australia	Australia-wide Note 2
Domestic Satellite Common View (DSATCV)	< ± 100 μs	< 1 part in 10^{10}	$3k	Eastern Australia	Unknown Note 3
Radio VNG	< ± 5 ms	< 1 part in 10^{10}	$1k	Usually Australia-wide, subject to ionospheric conditions	No change planned, but subject to funding
TV Synchronisation pulse (TV Sync)	< ± 10 μs	< 1 part in 10^{10}	$1k	Syd/Melb Metropolitan areas	No change planned Note 4
Telstra speaking clock	< ± 10 ms Note 5	< 1 part in 10^{8}	Domestic telephone	Australia-wide	Australia-wide
Telstra landline	< ± 1 ms Note 5	< 1 part in 10^{9}	Line rental	Capital cities	No change planned

Note 1: Available for frequency transfer January 1997
Note 2: After installation of NML monitoring system in WA and an assessment of accumulated data
Note 3: Change to digital satellite TV transmissions may make present system unusable
Note 4: Outside present coverage areas the use of MGPS is now recommended
Note 5: In and near capital cities

Table 1: Comparison of the methods for time and frequency transfer presently in use within Australia

Consequently, the inclusion of UTC(Aus) in the National Measurement Act will require the upgrading of certain aspects of the present time and frequency dissemination infrastructure. This upgrading will be needed to satisfy the requirements of those users who will wish, or be obliged, to refer to UTC(Aus) with sub-millisecond accuracy in a legally traceable manner, and also those users who will see opportunities for increased efficiency and productivity as a result of a clear and simple legal definition being provided for the time of day within Australia. NML has initiated the technical aspects of this upgrading, with the provision of traceable frequency dissemination in Eastern Australia using the multichannel GPS technique being one result. However, further work will be required, including extension of the multichannel GPS technique throughout Australia, and quantifying the propagation delays of signals from the Telstra speaking clock and Telstra landlines, especially in regions of Australia remote from Sydney and Melbourne.

CONCLUSION

The dissemination of time and frequency in Australia will continue to evolve, driven by user demand, technical advances, legal requirements and cost. During the next three years, the principal emphasis of NML's developmental activities in time and frequency dissemination are planned to be:

- To develop and install monitoring stations for GPS time and frequency at several points around Australia, in cooperation with other organisations as appropriate.

- To upgrade, driven by user demand, existing technologies presently used for legally traceable frequency transfer to also provide a corresponding time transfer function.

- To evaluate, develop and implement, in cooperation with other organisations as appropriate, newer time and frequency transfer technologies.

APPENDIX

A.1 Bureau Internationale des Poids et Mesures (BIPM)
The BIPM is the peak body of the Metric system, and is located in Paris.

A.2 Universal coordinated time (UTC)
UTC is a time scale derived by averaging the outputs of more than 220 atomic clocks around the world, including several Australian clocks[1],[2]. At irregular intervals, leap seconds are inserted into UTC to account for variation in the rate of the Earth's rotation.[3]

The data from the clocks contributing to UTC is collected and analysed by the BIPM Time Section. UTC is disseminated in the form of bi-monthly reports stating how many nanoseconds the one pulse per second (1 pps) outputs of reference clocks in each participating country are in advance or in retard of UTC.

Thus UTC is what is known as a *paper clock*, and there is no physical timing output. UTC can be *realised* by adjusting the timing of the 1 pps electrical output of a real clock to be *synchronised* with UTC to within the desired uncertainty.

A.3 UTC(Aus)
UTC(Aus) is the *Australian realisation* of UTC, and is presently the 1 pps output of a caesium clock maintained by the Australian Surveying and Land Information Group (AUSLIG). The 1 pps pulses from this clock are maintained to within ±1 µs of UTC. This tolerance can be improved as the need arises. It is likely that UTC(Aus) will ultimately be maintained at NML, although a date for this change has not been set.

A.4 The Système Internationale or (SI) second
Since 1968 the SI, or metric, second has been defined in terms of the caesium atom. The SI second can be realised by a commercially available *caesium frequency standard*, or *caesium clock*, typically with an uncertainty smaller than 5 parts in 10^{12}.

A.5 Global Positioning System (GPS)
The GPS, or NAVSTAR, system is a navigation system operated by the US Air Force. The principal component of the GPS system is a constellation of (normally) 24 satellites in Earth orbit. The position of every satellite in the constellation is known at any time to within a few metres, and each satellite contains at least one operating atomic clock. The satellites broadcast signals containing information on their location, as well as precision timing pulses. Receivers on Earth calculate their position using the satellite location information and the differences between the times of arrival of pulses from three or more satellites.

A.6 GPS Common-view time transfer (GPSCV)
This technique for performing clock synchronisation using the timing pulses from a single GPS satellite (figure 2) is analogous to two people synchronising their watches by listening to a sound within earshot of both, such as the report of a starting pistol. GPS common view time transfer receivers are relatively expensive (about $20000), mainly because of the small market. Although any satellite transmitting pulses may be used for common view time transfer, the GPS satellites have the advantage that they 'know' where they are, and broadcast this information. This facilitates the accurate calculation of the propagation path lengths between the satellite and the two receivers. The GPS common view technique is capable of an accuracy better than ±100 ns, limited by ionosphere-related variations in the propagation speed of the timing pulses from the satellites to the earth-based receivers[4].

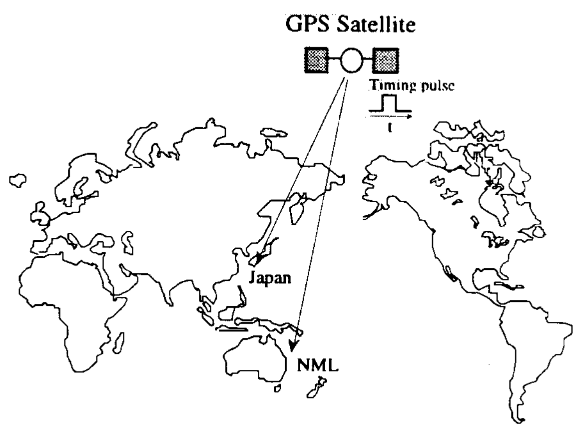


Figure 2: One of the many GPS common-view time transfer links used to compare clocks around the world, and to generate UTC. In this link, NML and its counterpart laboratory (the Communications Research Laboratory, CRL) in Japan observe particular timing pulses from particular GPS satellites, according to a schedule distributed by BIPM. Synchronisation of NML's clocks and Japan's master clocks is achieved by recording the local times of arrival of the same pulse transmitted by a satellite in view of both laboratories. A correction for the different path length from the satellite to the two laboratories is made based on the precisely known orbits of the GPS satellite. The data from both CRL and NML is transmitted weekly to BIPM, and is used in the calculation of UTC.

A.7 Two-Way Satellite Time Transfer (TWSTT)
A time-transfer technique where timing pulses are transmitted from one timing laboratory to another and back again, usually via commercial communications

satellites[5],[6]. This technique, although still under development, is far more accurate (better than ±10 ns has been demonstrated, with potential for better than ± 1 ns) than GPS time transfer because its two-way nature allows the propagation time of the pulses between the laboratories to be measured directly. Because it is necessary to both transmit and receive the timing pulses, the required equipment, including a satellite communication dish, is far more expensive (in the region of $150000) than that required for the GPSCV technique. Furthermore, charges for the use of the commercial communications satellites are significant. Consequently the technique is presently suitable only for time transfer between major national timing laboratories such as NML.

A.8 Multichannel GPS receivers (MGPS)

In contrast to the GPS common view time transfer receiver, the multichannel GPS receiver is essentially a slightly modified mass-produced navigation receiver which 'looks' at signals from as many as eight satellites in view at any given time. MGPS receivers report GPS time, which is the reference time scale of the GPS system. GPS time is maintained within a known offset of UTC, however the value of this offset is not of particular importance for navigation purposes (but of course it is for timing purposes), and may be changed at the discretion of the US Air Force. Consequently, monitoring of GPS time within Australia is necessary to ensure traceability to UTC(Aus). Furthermore, this monitoring must be carried out at several locations across Australia to ensure that the time and frequency measurements of users are not compromised by malfunctioning GPS satellites being in view of their receivers.

NML presently monitors GPS time in Sydney and Canberra (with the cooperation of AUSLIG), and plans to extend this service to Melbourne, Adelaide and the Perth region.

Some MGPS receivers suitable for time transfer cost less than $1000, and appear to be capable of time transfer accuracy better than ±1 μs for a single reading.

A.9 GLONASS

The GLONASS system is a Russian satellite based navigation system similar to the GPS system. GLONASS time transfer receivers have recently become available.

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