STATUS OF ACTIVITIES AND PLANS FOR PRECISE TIME COMPARISONS IN AUSTRALIA

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ABSTRACT

The routine use of artificial satellites has revolutionised precise time comparisons in Australia in this decade. Global Positioning System (GPS) time transfer units are operating in Sydney, Melbourne, Canberra, Alice Springs and Yaragadee (Western Australia) and provide the major link between the atomic clocks in those centres. They also provide the link with international time scales on a daily basis, superseding the clock trips from the USA every three months or less frequently.

A project is being developed to use TV transmissions from the Australian domestic satellite AUSSAT for comparisons over a large part of the country to replace the terrestrial TV system which is no longer useable for this purpose. The possibility of inserting an on-time signal in the AUSSAT TV transmission is also being studied. An experiment to compare clocks in Sydney with clocks in Japan and other countries in the Far East is under way, using the Geostationary Meteorological Satellite (GMS).

1. HISTORICAL BACKGROUND

The first recorded visit by a commercial atomic standard to Australia occurred in 1959 (Blair 1974), followed by one in 1967 (Bodily and Hyatt, 1967). Also in that year Australian institutions took delivery of their first commercial caesium standards. From then on, flying clock measurements were conducted on a regular basis until February 1986. Interpolation between clock trips could not be done satisfactorily to atomic clock precision by HF time signals, so reception of VLF transmissions from GBR, NWC, NLK, Omega and others sources became common.

In 1969 the first TV experiments were conducted between Sydney and Canberra, in which Australian Broadcasting Commission programs were received from a "common view" transmitter in Wollongong, a city that is roughly equidistant from the two cities (Miller, 1970). The TV measurements were initially designed to help verify the interpolation process, but with the realisation that some programs were networked over constant bearers to large parts of the country, the method grew rapidly until, by 1980, substantial areas of all states except Western Australia were linked by a homogeneous, sub-microsecond system (Figure 1). A particular impetus was given by the introduction of colour TV in 1975, which improved measurement precision to 50 nanoseconds or better. For many users, the connection provided by TV to the central standards at the CSIRO Division of Applied Physics (National Measurement Laboratory), Telecom Australia Research Laboratories and the Division of National Mapping's observatory at Orroral (to use their current names) proved more than adequate, while the inclusion of the standards in the NASA tracking stations at Tidbinbilla and Orroral Valley strengthened the network considerably.

To ensure the co-ordination of the many possible combinations of TV comparisons, the Division of National Mapping undertook in the early 1970s to calculate a time scale known as UTC (AUS) using an algorithm similar to ALGOS developed at the Bureau International de l'Heure (BIH, 1973). The first Australian-owned portable caesium clock was delivered in 1972, and has been used regularly to calibrate the TV bearer delays in support of UTC (AUS). This time scale has proved to be a rather better interpolator for UTC than VLF measurements. The installations contributing to UTC (AUS) are given in Appendix 1.

Since July 1973, experiments in time transfer using NTS and GPS satellites have been carried out (Easton et al., 1973; Buisson et al., 1976; Luck et al., 1983) and these have formed the basis for the system described in the remainder of this paper.

2. TRANSITION TO SATELLITE TV SYSTEM

The National Standards Commission is the Australian body with the statutory responsibility for coordinating the national measurement system. As a result of seminars held in September 1982 and August 1983 several areas of concern were identified; one being the provisions for precise time comparisons throughout Australia.

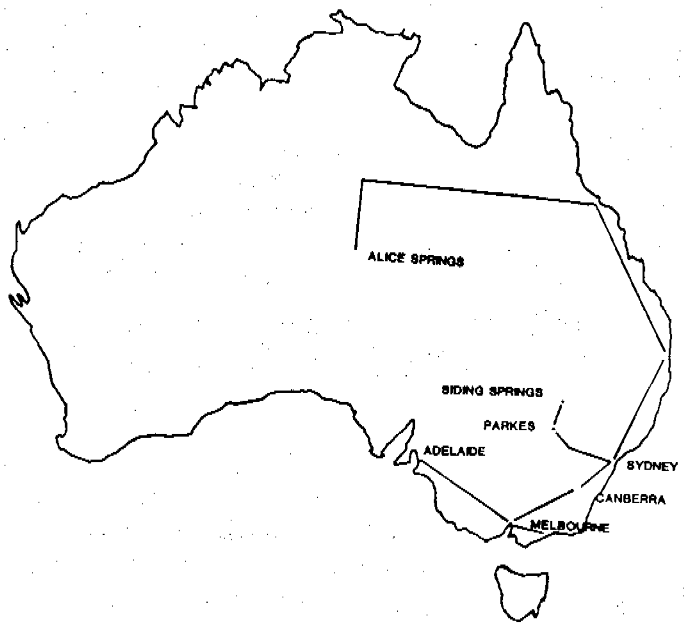

Figure 1: The Australian terrestrial TV network, 1980.

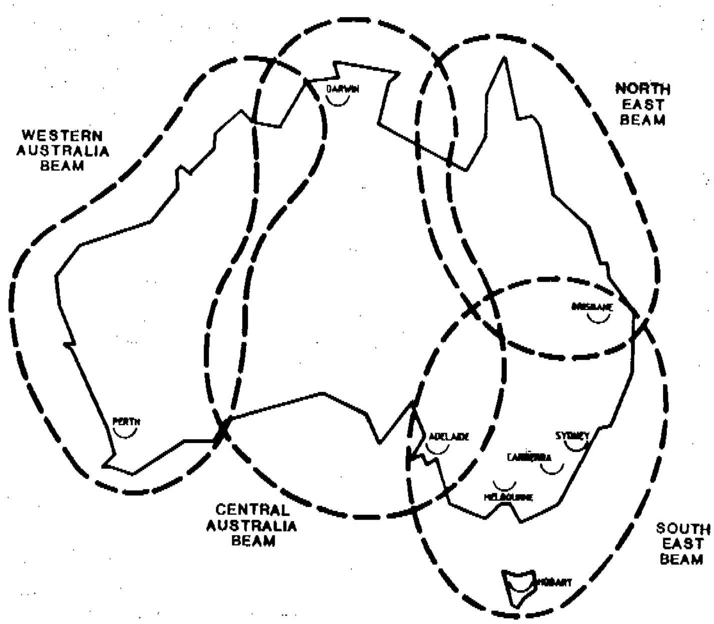

Figure 2: Footprints covered by separate transponders of the national domestic satellite AUSSAT.

The time-keeping community in Australia had for some time relied upon terrestrial TV signals as a convenient medium for making simple and inexpensive time comparisons. However, the advent of TV broadcasting using the AUSSAT satellite by the Australian Broadcasting Commission meant that the terrestrial system could no longer be used.

It was timely therefore for the National Standards Commission to arrange a technical workshop on precise time comparisons. The workshop, held in February 1984, reviewed the present and future user needs and the means for making time comparisons. One of the outcomes of the workshop was the formation of a working group to consider, amongst other things, the use of satellite systems to replace the ABC terrestrial system.

In its report in February 1985, the working group recommended that the Global Positioning System (GPS) be adopted as the basis for future time comparisons in Australia. Since GPS time transfer units are relatively expensive and available only at major centres within Australia, inexpensive methods of time transfer using the domestic satellite were also considered. In May 1986 the working group recommended the use of ABC TV signals from AUSSAT for general use at remote locations. An interim schedule for observations was circulated to all members of the Australian time-keeping community.

3. GPS FOR NATIONAL AND INTERNATIONAL LINKAGES

The GPS of navigational satellites is now utilised to provide precision timing links between centres in Australia using common view observation of individual satellites of the GPS constellation. Timing centres in Sydney, Melbourne and Canberra intercompare their time and frequency standards by this method, and at present use the GE MK III system for the interchange of data. These data are subsequently coordinated by the Division of National Mapping in Canberra. Using this technique, time coordination between these centres is achieved to better than 30 nanoseconds. As other GPS equipped stations in Australia become established they will, where possible, be incorporated into this timing network.

GPS timing receivers operate in a programmed sequence of timing observations as recommended by the National Bureau of Standards. This sequence caters for both national and international common view links. The individual satellite clocks are also used to achieve an indirect and less accurate timing link to the USNO.

The programmed sequence of GPS satellite common view observations links Australia to the international timing community via the Radio Research Laboratory (RRL), the Tokyo Astronomical Observatory in Japan and WWVH in Hawaii. The link to the RRL provides comparative data for a collaborative project with the National Measurement Laboratory in Australia using the navigational tones of the Geostationary Meteorological Satellite (GMS) for time transfer.

4. AUSSAT TV SIGNALS FOR TIME COMPARISON

The first satellite of the Australian Communications Satellite System AUSSAT was launched on 27 August 1985, and the second was launched on 27 November 1985. A third satellite is scheduled for launch early in 1987.

AUSSAT K1 is in geostationary orbit at 160° east longitude, and transmits in the K_u band. TV programs are transmitted from 30 watt transponders to "footprints" covering separate portions of the country as shown in Figure 2. An earth station with 1.5 metre antenna is generally sufficient to receive excellent pictures, but a decoder is necessary to convert the signal, which is B-MAC encrypted, to PAL. A receive-only earth station including 1.5 metre antenna, low-noise amplifier and B-MAC decoder retails for about $A2000, and is well suited for precise time comparisons. The same sync pulse separator as used in the conventional terrestrial TV receiver is adequate, but a refined version that takes as input the signal before decoding gives much better results, with jitter less than 10 nanoseconds.

A schematic diagram of the measurement arrangement is shown in Figure 3. Measurements of time interval typically show a diurnal variation with an amplitude of 60 microseconds and with discontinuities corresponding to orbit manoeuvres of the satellite as shown in Figure 4.

Comparisons made between Sydney and Melbourne, show that time transfer can be accomplished with microsecond precision (see Figure 5), while accuracy would depend on occasional portable clock calibrations to correct for the average differential effects of the AUSSAT orbit. When the results are corrected for the propagational delay, computed from the Kepler elements of the orbit, the residual diurnal variation is still appreciable at the 200 nanosecond level, but the noise is very much less (see Figure 6).

Methods for the provision on the satellite television transmissions of epoch related to the time standards of the National Measurement Laboratory are under development.

Where the time difference has been determined independently by GPS time transfer, the AUSSAT data from various sites may be used to calculate the position of the satellite and hence corrections to the Kepler elements provided by AUSSAT. This work will become more productive with the addition of stations at Adelaide and Perth capable of receiving both AUSSAT TV and GPS, as the present stations in Sydney, Canberra and Melbourne are nearly co-planar.

5. OTHER METHODS FOR TIME COMPARISON

5.1 Geostationary Meteorological Satellite

An experimental collaborative project to utilise the Japanese Geostationary Meteorological Satellite (GMS) for experimental time comparisons between the Radio Research Laboratory in Japan and the National Measurement Laboratory in Australia is continuing (Morikawa et al., 1986). This time transfer method utilises the trilateration ranging tones which are used for satellite position determination. The ranging tones at 200 kHz are simultaneously intercompared with time standards at each laboratory at a time when the satellite position is accurately determined. The potential time transfer capability of the order of 30 nanoseconds may not be realised due to difficulties in the determination of geodetic position and system time delays. GPS common view time comparisons supplement this experiment.

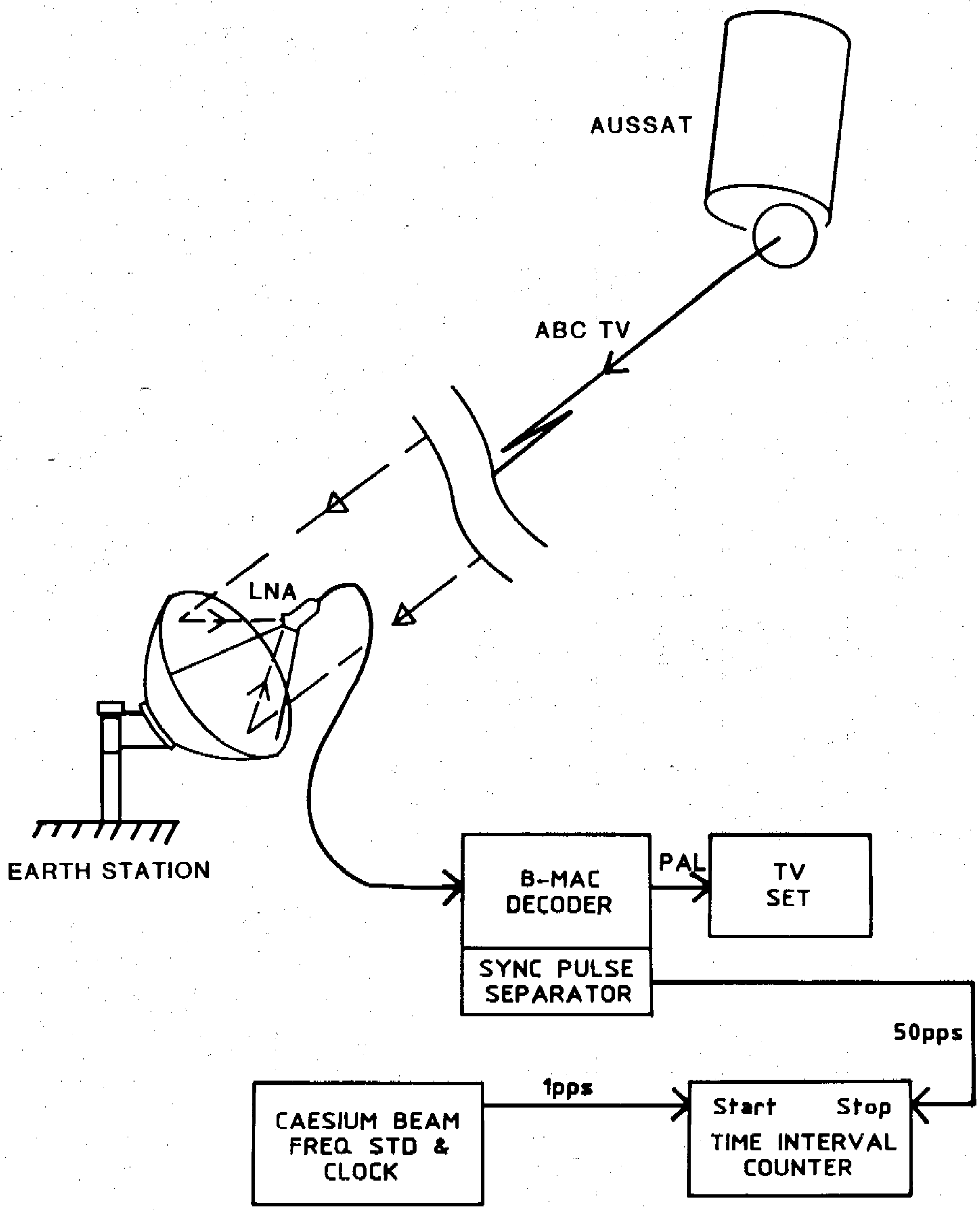

Figure 3: Measurement system for precise time comparisons using TV signals from AUSSAT.

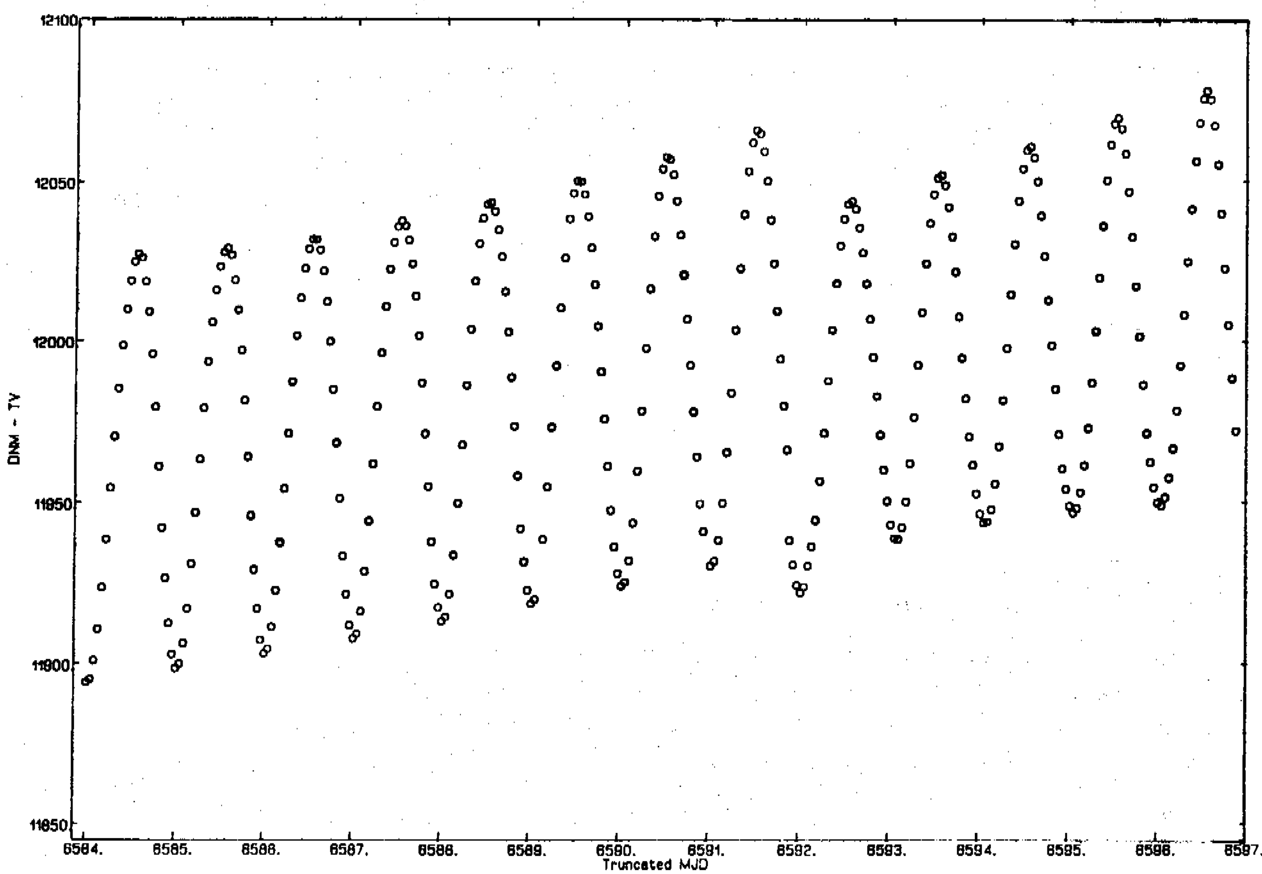

Figure 4: Raw hourly measurements of TV sync pulse from AUSSAT referenced to Cs 590 at Orroral (DNM).

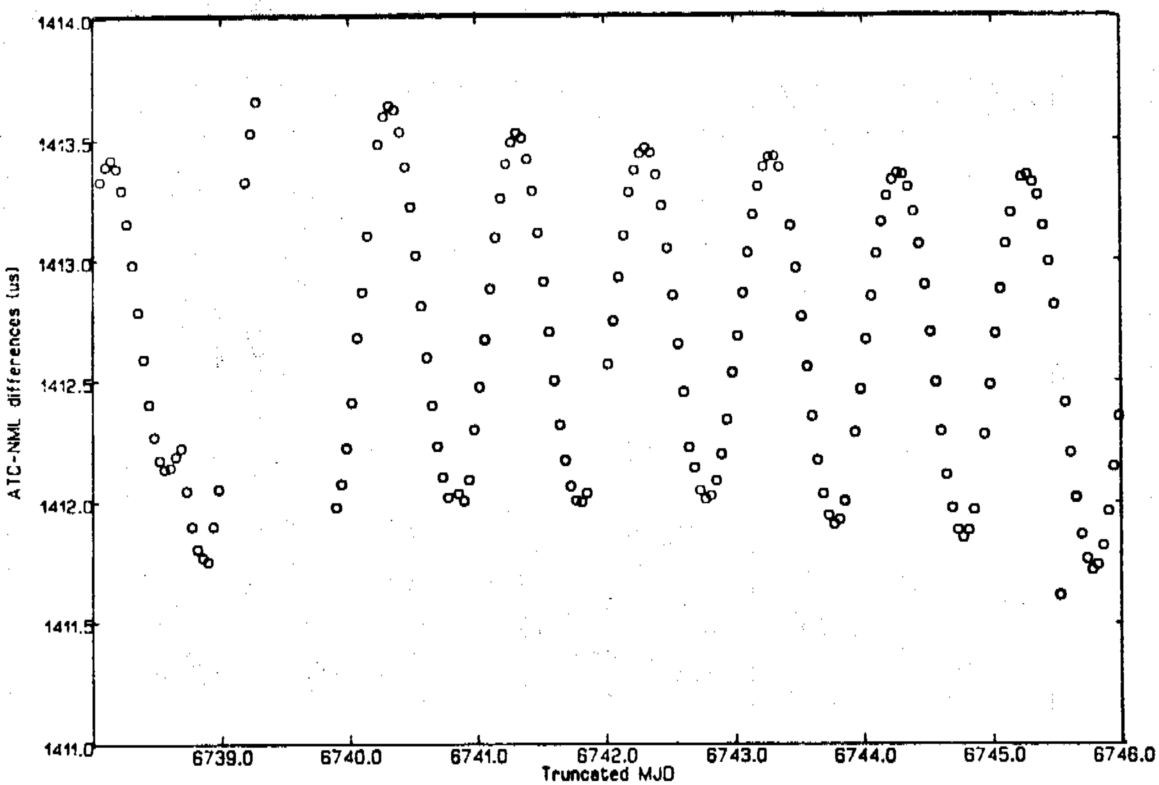

Figure 5: Differences of raw hourly TV sync pulses from AUSSAT measured at Melbourne (ATC) and Sydney (NML), corrected for reference clock differences determined by GPS time transfer.

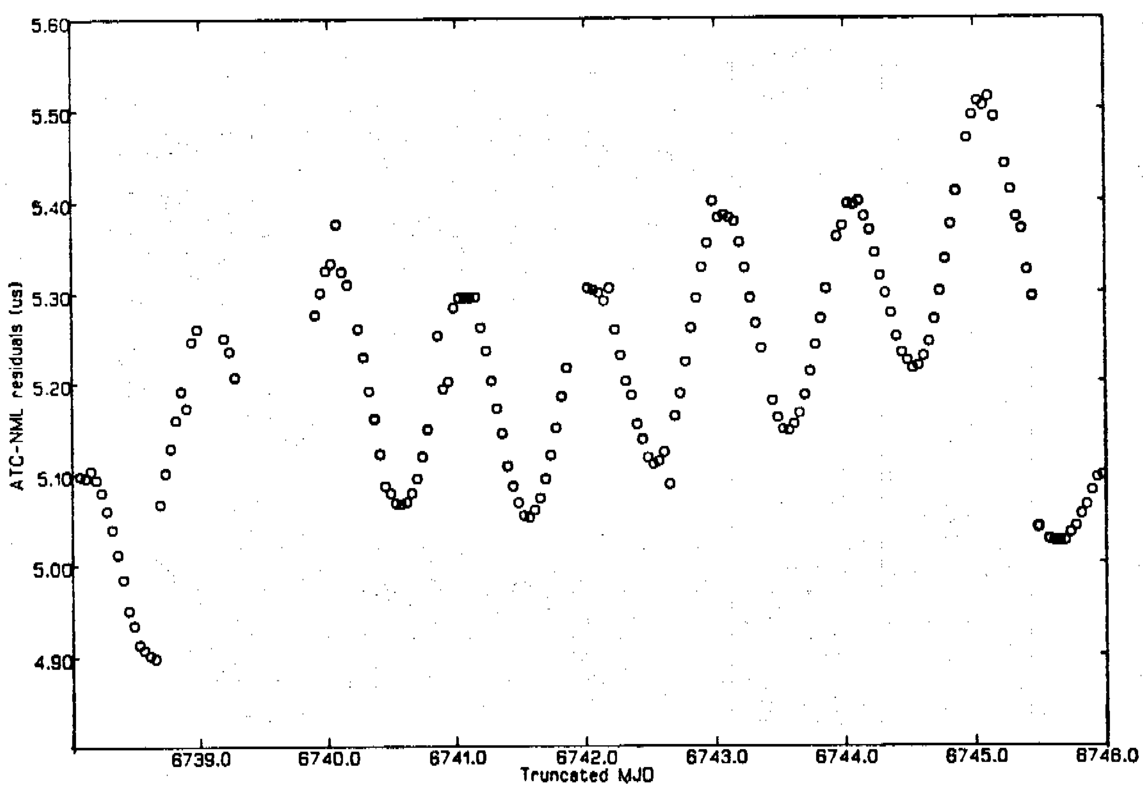

Figure 6: As in Figure 5, with range differences obtained from nominal Kepler elements of AUSSAT removed.

5.2 Terrestrial TV Time Transfer

Within cities or regions served by a common TV transmitter, local TV will continue to be used. This means that laboratories within Brisbane, Sydney, Melbourne, Hobart and Adelaide can continue to use TV time transfer within their own cities. Terrestrial TV links will continue in Victoria and Tasmania and there is a terrestrial link between Melbourne and Adelaide so that time intercomparisons can continue in the previous manner.

5.3 Telecom Services

The Australian Telecommunications Commission (ATC) is the chief distributor of standard time and frequency within Australia, which it generates from its independently calibrated standard time and frequency installation, operated by the Research Laboratories at Clayton, Victoria, both for its own purposes and for use by the public. Standard time and frequency signals are distributed by cable pairs, broadband bearers and radio transmissions. Receivers for all these distributions are commercially available.

The ATC services have been described in detail (Harris, 1985) and include the following:

- A civil time distribution system where the time is transmitted in BCD form to any part of the Telecom network. The accuracy obtained using this system is $\pm$ 500 microseconds.

- A landline distribution of two tones at 1.7 kHz and 2.7 kHz where the 1 kHz tone difference is derived from a frequency standard. Short term (10 seconds) frequency measurements are limited by noise to one part in 10^7, but long term measurements readily achieve parts in 10^{11} in a day.

- A controlled oscillator, containing a high precision quartz crystal, phase-locked to the two-tone system, by which the problems of fast phase jitter and interruptions are overcome. A unit designed by Telecom stores the control voltage so that, on failure of the reference signal, there is no significant step change in frequency. The frequency is maintained to better than one in 10^{11} of Telecom's frequency standard during controlled operation, and to within five in 10^{11} when the reference fails.

- Standard frequencies of 1 kHz in capital cities, plus 10 kHz and 100 kHz in Melbourne and Adelaide, are derived from the two-tone system and distributed by cable to specific customers. In addition, all customers of Telecom Australia's Digital Network will have access to the network synchronisation system at their terminals, with frequencies accurate up to one in 10^{11} depending on transmission media and exchange variations.

- Radio station VNG that transmits time signals that are maintained within 10 microseconds of UTC (ATC). It transmits on three frequencies, on a schedule to give reliable coverage of most of Australia.

7. CO-ORDINATION

Three functions of precise time have traditionally been divided between three civilian organisations in Australia. The statutory authority for maintaining the national standard of time interval and frequency is the National Measurement Laboratory of the CSIRO Division of Applied Physics, in which task they are assisted by Telecom Australia Research Laboratories and the Division of National Mapping as agents under the National Measurement Act (1960).

The Division of National Mapping accepted the function of determining astronomical time upon transfer of the National Time Service from Mount Stromlo and Siding Spring Observatories in 1971. It performed this role through stellar observations with a PZT until 1985, and continues to perform it by satellite and lunar laser ranging, contributing to the work of the BIH. Telecom has accepted the role of disseminating time signals in the UTC system through VNG and its several landline services, as they are required for its own telecommunications purposes.

In addition, many military and industrial laboratories are required to trace their frequency standards back to the national standard, while astronomical observatories, particularly those observing pulsars, quasars and laser targets, need international synchronisation of a high order.

The task of co-ordinating these activities has therefore been essential in the interests of national efficiency in a country of this size, but has been made simpler by the small population enabling relatively informal mechanisms to be applied. The Division of National Mapping has promoted co-ordination by collecting data and collating them in the form of UTC (AUS) as published monthly in Bulletin E. This gives the relationship between UTC (AUS) and UTC (USNO MC) as well as the relationship between UTC (AUS) and participating clocks, thus satisfying all but the most immediate requirements for international co-ordination. Figures 7 and 8 show the performance of UTC (AUS) in recent years.

Since 1984, a selection of Australian clocks filtered through UTC (AUS) has been used in the formation of TAI by the BIH. This has been due to the availability of routine GPS time comparisons.

A variety of data communications media have to be used. All fast international communication is by GE Mark III, supplemented by the regular bulletins posted by USNO and BIH. Within the country, GE is used but little, the bulk of data being sent by telex, letter and floppy disc. The Telememo electronic mailbox system recently implemented by Telecom Australia is being tested at the moment, and there are possibilities that AUSSAT services may become available at reasonable cost, especially for the more remote locations.

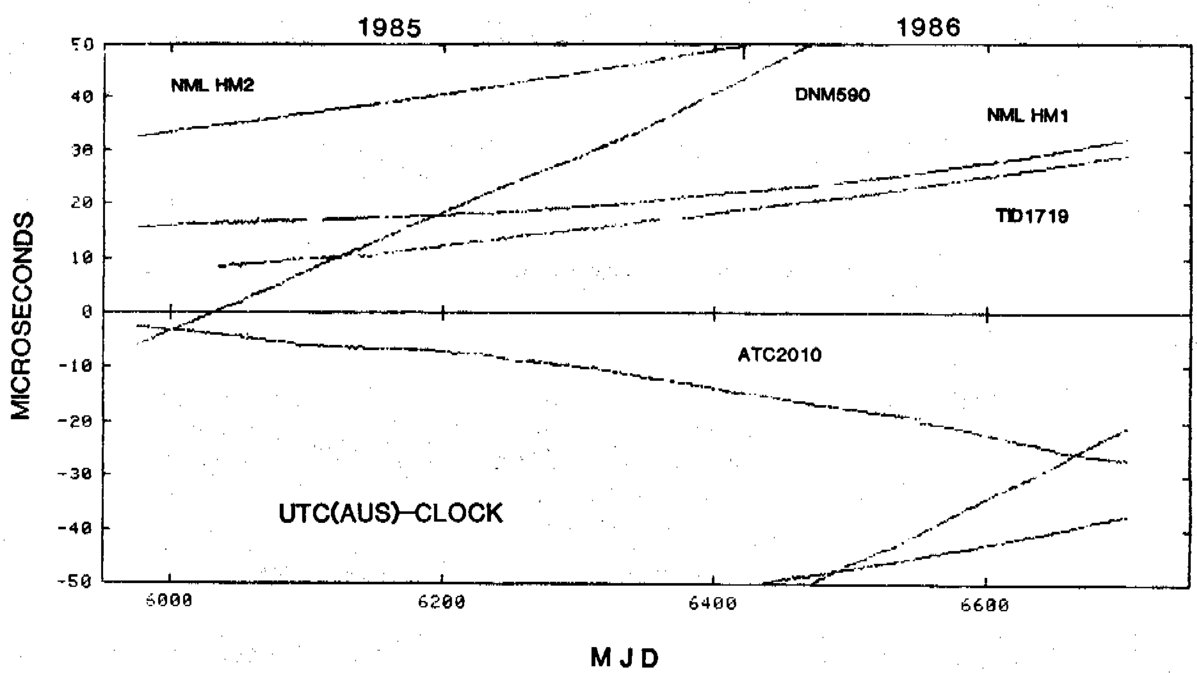

Figure 7: Performance of a selection of clocks contributing to UTC (AUS) during 1985-86.

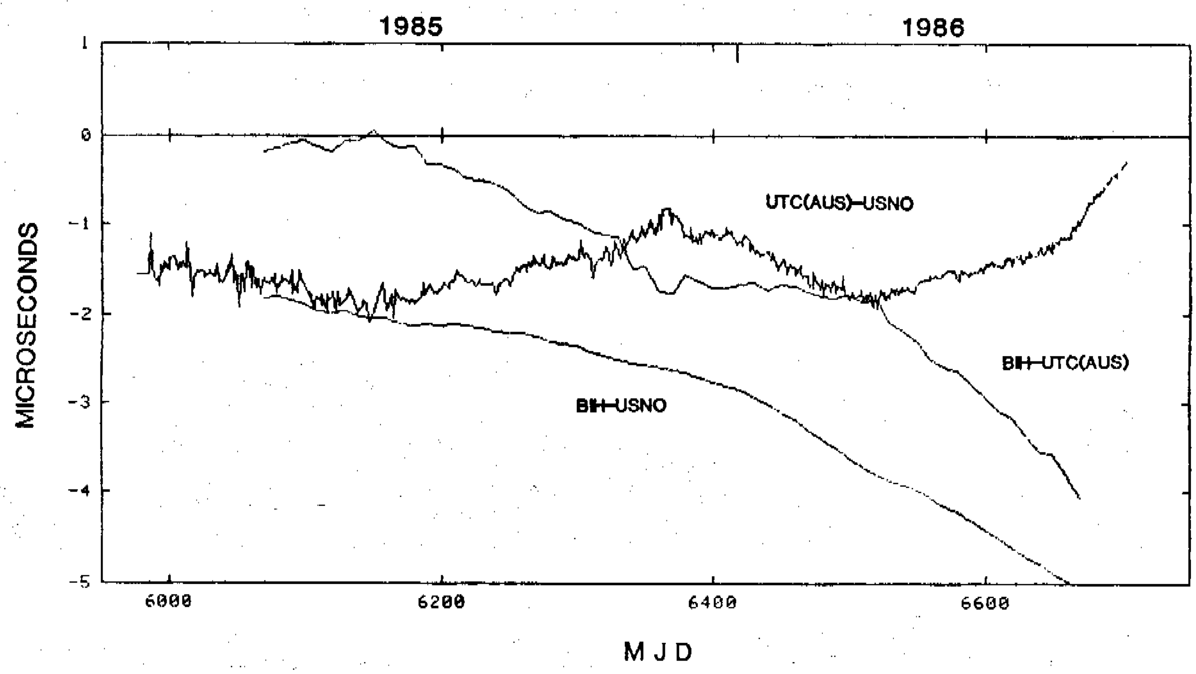

Figure 8: Performance of UTC (AUS) in 1985-86. Daily values against UTC (USNO MC) are derived from GPS measurements and USNO Series 4. 10-day values against UTC (BIH) are derived from BIH Circular D.

Only three general meetings of interested people have been held in the last 20 years. In 1972, a group met at the Division of National Mapping to discuss the formation of UTC (AUS). The Institution of Radio and Electronics Engineers Australia conducted a Precise Time and Frequency Conference in 1980, which attracted some international participation and led to the National Standards Commission technical workshop in 1984. The working group formed at that workshop also acts as a National Study Group for CCIR Study Group 7, communicating through the Commonwealth Department of Communications.

8. CONCLUSION

Precise time comparisons by GPS are used daily in several Australian localities to relate clocks to UTC. The techniques used include both "common view" with Japan and Hawaii, requiring a second leg to relate to UTC(USNO) and UTC(NBS), and "longarc" using SV clocks as interpolators of UTC(USNOMC). The GPS measurements are supplemented by GMS experiments relating Sydney to Japan.

The GPS measurements within Australia are now the basis for computing the national time scale UTC(AUS). Within those cities where GPS receivers are located, terrestrial TV is used for local clock comparisons, enabling more clocks to contribute to the time scale and providing a monitoring service.

A system based on TV signals from the domestic satellite AUSSAT is being developed to permit clock comparisons at moderate cost over much of the country previously linked by the terrestrial TV networks. GPS measurements will support a small orbit determination network which should give sub-microsecond capability to the AUSSAT TV system.

Time signals based on UTC are disseminated by Telecom Australia from high frequency radio station VNG and through its telephone network. A scheme to impress a time signal on AUSSAT nationwide TV transmissions is being studied.

These activities are co-ordinated by a working group on the National Standards Commission.

APPENDIX 1

Installations contributing to UTC (AUS)

The installations contributing to UTC (AUS) and participating in the GPS/TV network are given below. These generally use commercial caesium standards, high quality crystals or rubidium standards. The Deep Space Communications Centre DSCC 42/43 at Tidbinbilla operates two SAO hydrogen masers, models VLC 10 and 11, while CSIRO National Measurements Laboratory in Sydney has wholly designed and constructed two hydrogen masers which operate in tandem as excellent clocks (Hibbard, 1967).

Within Sydney, Canberra and Melbourne a number of users participate using local TV. The connections to Hobart (Tasmania), Adelaide (South Australia) and central New South Wales are tenuous at present, since the plan to use TV from the domestic satellite AUSSAT is not yet in place. It is hoped that Perth (Western Australia) may be included in the network, since the Goddard Laser Tracking Network station at Yaragadee is connected to South-Eastern Australia by GPS and is also well placed to monitor the appropriate TV transmissions from AUSSAT. Similarly, a GPS time transfer capability at the Smithfield TRANSIT/GPS tracking station near Adelaide would cement that city into the network.

The distribution of the timekeeping centres is illustrated in Figure 9.

ESTABLISHMENT	FREQUENCY STANDARDS	COMPARISONS
(i) Co-ordinating Centres		
CSIRO NML Sydney	1 HP Cs 5061A 1 HP Cs 5060A 2 H Masers	Terr TV, Aussat TV GPS, GMS, Goes, Transit
Division of National Mapping	4 HP Cs 5061A 1 HP Cs 5060A	Terr TV, Aussat TV GPS
Telecom Research Laboratories	6 HP Cs 5061A 1 HP Cs 5060A 1 HP Rb 5065S	Terr TV, Aussat TV GPS
(ii) Participating Centres		
University of Queensland	1 HP Cs 5061A	Terr TV
ABC Brisbane	1 HP Rb 5065A	

Department of Defence GWESF	1 HP Cs 5061A	Terr TV
Naval Electronic Calibration Laboratory	1 HP 5061A	Terr TV
Royal Australian Air Force	2 HP 5061A	Terr TV
Philips	1 HP Cs 5061A	Terr TV
Department of Transport	1 HP Cs 5062C	Terr TV
ABC Sydney	1 HP Rb 5065A	
University of NSW SCCML	1 HP XTAL	Terr TV
Department of Science CDSCC Tidbinbilla	3 HP Cs 5061A 2 H Masers	Terr TV, GPS Microwave to Parkes
CSIRO Parkes	1 HP Rb 5065A	Microwave to Tidbinbilla, Terr TV
Department of Science AAT Siding Spring	1 XTAL	Terr TV
Australian National University Siding Spring	1 XTAL	Terr TV
Hewlett Packard Melbourne	1 HP Cs 5061A	Terr TV
ABC Melbourne	1 HP Rb 5065A	
Telecom Adelaide	2 XTAL	Terr TV
Department of Defence DRC	1 HP Cs 5061A 1 XTAL	Terr TV
Department of Defence Tranet 412	2 HP Cs 5061A 1 HP Rb 5065A	Terr TV
ABC Adelaide	1 HP Rb 5065A	
Department of Defence Woomera	1 HP Cs 5061A	SATCOM
Department of Defence JDSRF Alice Springs	3 HP Cs 5061A	GPS
Perth Observatory	1 HP Rb 5065A 1 XTAL	

Department of Transport Perth	1 HP Cs 5062C	
University of Western Australia	1 XTAL	
ABC Perth	1 HP Rb 5065A	
Department of Science Moblas Yarragadee	2 HP Cs 5061A	GPS, LORAN-C
University of Tasmania	1 Rb	Terr TV
ABC Hobart	1 HP 5065A	

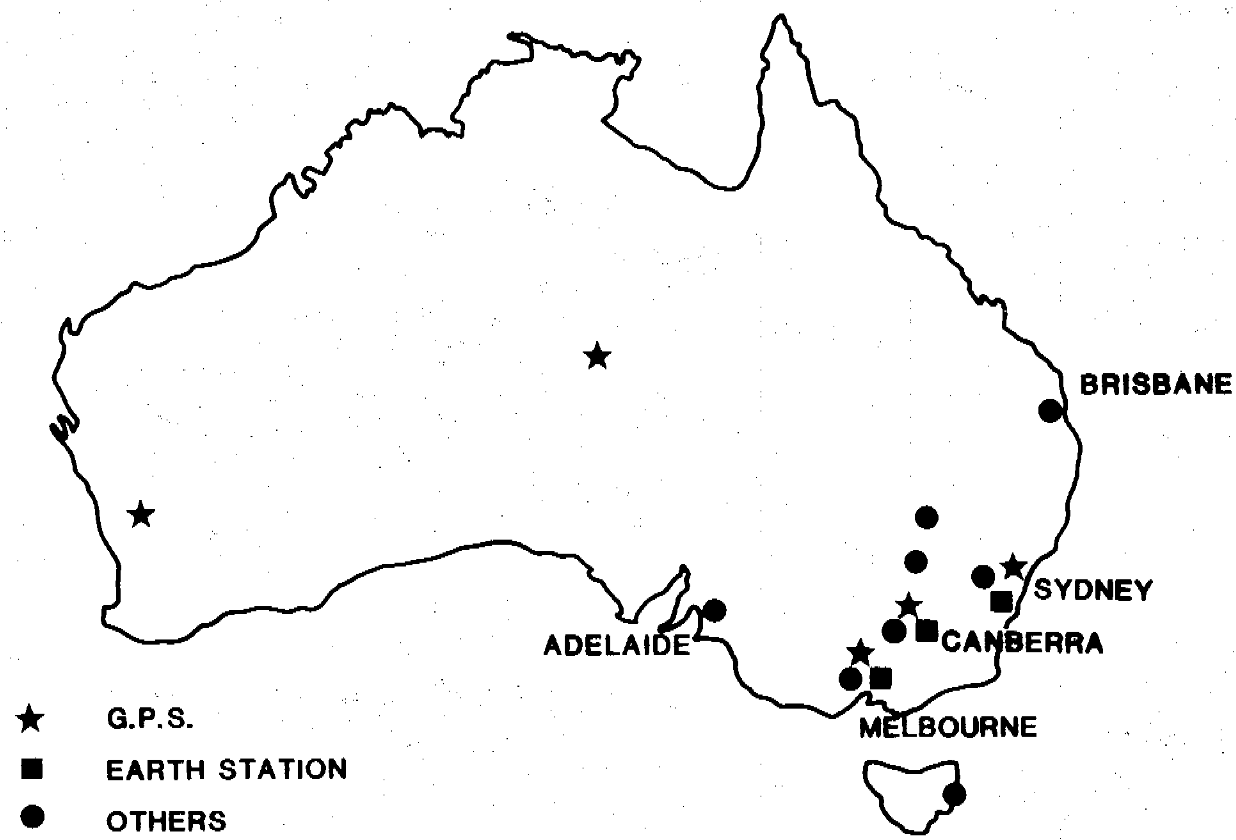

Figure 9: Distribution of stations using GPS, AUSSAT TV and terrestrial TV derived from AUSSAT, December 1986.

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