TIMING SYSTEMS FOR ATNF TELESCOPES

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Abstract

Radio Telescopes require precise time and timing signals for accurate telescope pointing, synchronisation of signal processing instrumentation and offline manipulation of observation data. We provide an overview of the timing system in use at our observatories; briefly describing the main features of the hardware, firmware and software.

INTRODUCTION

The Australia Telescope National Facility, (ATNF) comprises the observatories located near Parkes and Narrabri in NSW and the Murchison Radio Observatory (MRO) in remote Western Australia. The Commonwealth Scientific Industrial Research Organisation (CSIRO) division of Astronomy and Space Science (CASS) manages and operates the ATNF primarily for astronomical research conducted by scientists from institutions in Australia and around the world.

Our radio telescopes vary in age and architecture: from the Parkes 64m single dish (1961), to the Australia Telescope Compact Array (ATCA) (1988) near Narrabri NSW, an array of 6 x 22m diameter moveable antennas, to the Australian Square Kilometre Array Pathfinder (ASKAP) at the MRO, an array of 36 x 12m antennas currently in the outfitting and early commissioning stage of construction. While ASKAP employs the latest technology, our older telescopes have been kept at the forefront of astronomical research due to continual upgrades to their instrumentation and extension of their operating capabilities.

Observations are made with the Compact Array and Parkes 64m telescopes both separately and together to form the Long Baseline Array. Occasionally, the array is extended further with radio telescopes in Tasmania and New Zealand. The technique of using widely separated telescopes in concert provides increased resolution and hence greater detail in the final astronomical images and is known as Very Long Baseline Interferometry (VLBI). Precise time and timing signals are required to synchronise instruments within a single antenna, between antenna elements of an array and between widely separated sites.

Figure 1 illustrates the basic instrumentation of a radio telescope and the points where time and timing signals are applied. Referring to Fig. 1: extremely weak radio frequency energy from a celestial source is converted to an electrical signal and amplified by a multi-band receiver mounted at the focal point of the antenna. The signal is then frequency down-converted and band-pass filtered before being sampled and digitised and passed to the correlator for correlation with itself, and, in the case of an array, with the signals from other antennas. The frequency conversion system requires local oscillators to 'tune' the receiver to the chosen centre frequency within each band and usually other fixed local oscillators for further stages of down conversion to an Intermediate Frequency (IF) suitable for digital sampling. All local oscillators must be precisely controlled to maintain constant phase and phase coherence between the converted signals. Lack of phase coherence results in a reduced output level at the correlator and therefore reduced sensitivity. Phase jitter reduces the quality of the final astronomical image [1]. To this end, the antenna-based oscillators are phase-locked to a highly stable central reference oscillator. In the case of an antenna array, small variations in reference phase at an antenna can occur due to movement and temperature changes in the distribution cabling. These are compensated by measuring the round-trip phase from a central point to each antenna and back; applying corrections either to the correlator output data or to the phase of the local oscillator at the antenna [1].

To attain sufficient dynamic range, the correlator accumulates the correlated input data streams for an 'integration cycle' period, of typically 5 or 10 seconds, prior to transformation to the frequency domain [1]. The integration cycle waveform, along with other real-time sequencing events supplied to the correlator, is generated by an ATNF 'Event Generator'. A Master Clock supplies precise current time to the Event Generator which is pre-programmed to set or clear its digital output event lines at absolute times corresponding to waveform transition edges.

The Antenna Control Computer also uses an Event Generator to generate the 'Start of Integration' events for the Digitiser and the 'Calibration Cycle' waveforms for the Receiver and Conversion System. Start of Integration is encoded in the IF data streams produced by the Digitiser and used to implement variable delays between the signals from an antenna array. The delays are added to compensate for the different arrival times of a celestial signal at each antenna and varied as the earth rotates to ensure alignment of samples from the same wave-front [1]. This concept is illustrated in Fig. 2 below.

The Calibration Cycle is used to determine the overall system gain and hence the true flux of the celestial source. (The system gain itself varies automatically to provide a constant input level to the samplers.) The Calibration Cycle waveform modulates a noise source of known power amplitude at the input to the receiver. The Conversion System then measures the noise on / off power levels and the difference is used to determine the gain [1].

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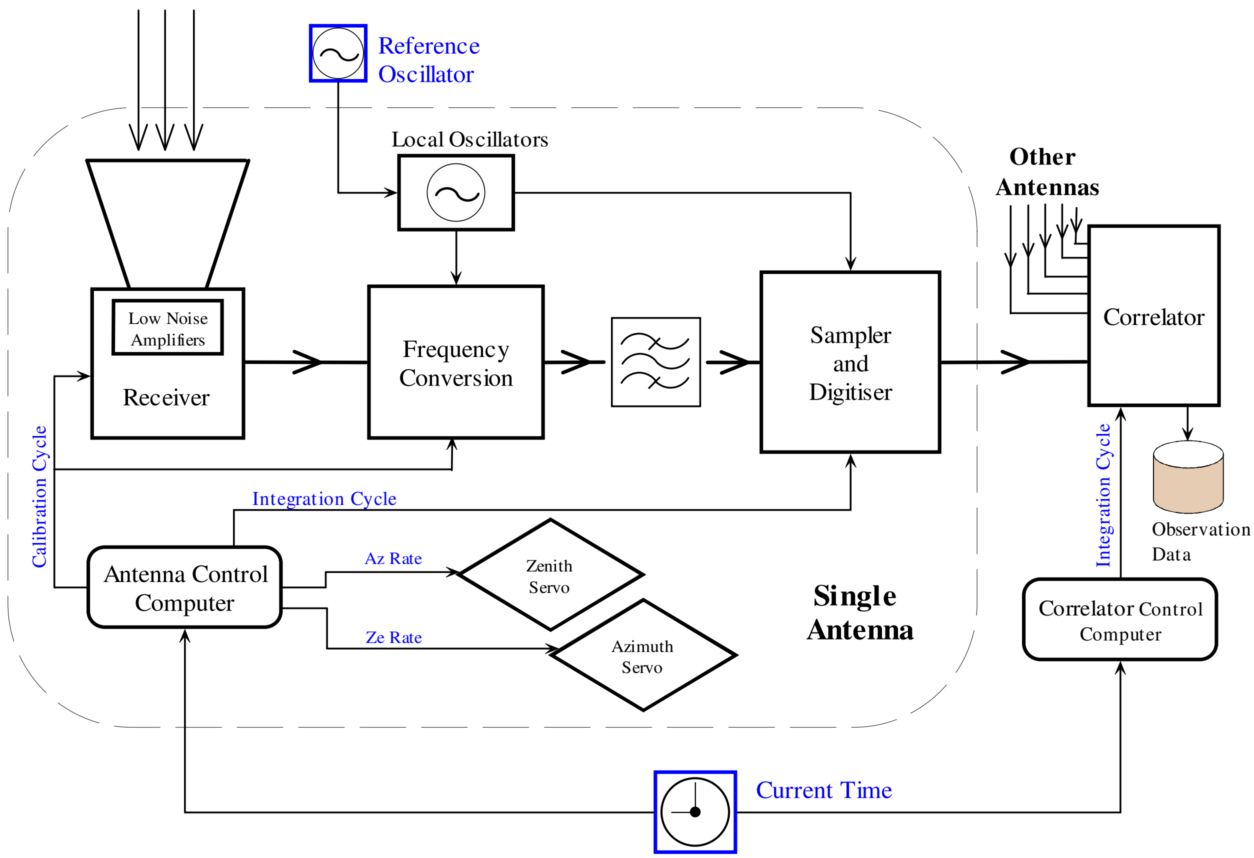

Figure 1: Radio telescope basic instrumentation.

An Event Generator is also used to synchronise a software control loop that supplies the antenna axis drive servos with azimuth and elevation coordinates to execute an antenna pointing trajectory in scanning or tracking a source. The antenna pointing coordinates themselves are determined from the current Universal Coordinated Time, the geographic coordinates of the observatory site and the Right Ascension / Declination of the source [1].

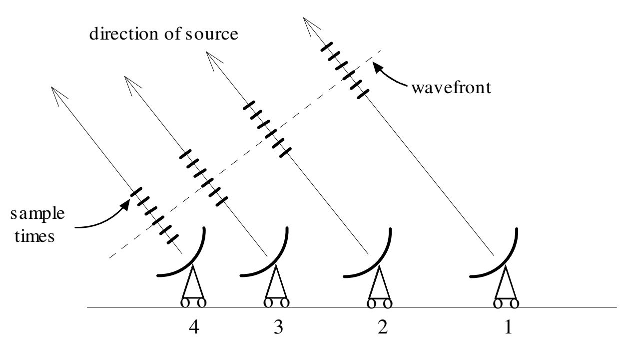

Figure 2: The wave-front concept [1].

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[1] Reproduced from a drawing by Wilson W., (CASS, retired), published in [1]

TIMING SYSTEM BASIC ARCHITECTURE

Figure 3 below illustrates the basic architecture of the timing system in use at each ATNF telescope site.

A central Hydrogen Maser / Reference Oscillator provides the highly stable reference frequency, (typically 5 MHz), to phase-lock the antenna local oscillators and an ‘ATNF Distributed Clock’ (ATDC). The purpose of the ATDC is to generate and distribute time signals to time dependent equipment throughout an observatory site [2]. Time information is encoded in a bit stream, the ‘Clock Frame’, and transmitted once per millisecond over fibre optic cable or balanced copper pairs and is commonly referred to as ‘Clock Bus’. The ATDC divides the input reference oscillator frequency in stages to produce a one pulse per second (1pps) output. An external 1pps from a GPS Receiver[2] provides a reference ‘tick’ input to the ATDC for comparison with its own 1pps. The difference, the ‘Tick Phase’, provides a fine-grain measure of the accuracy of the clock. In short, the GPS 1pps is the common timing reference between sites and the Reference Oscillator is the source of precision timing at each site.

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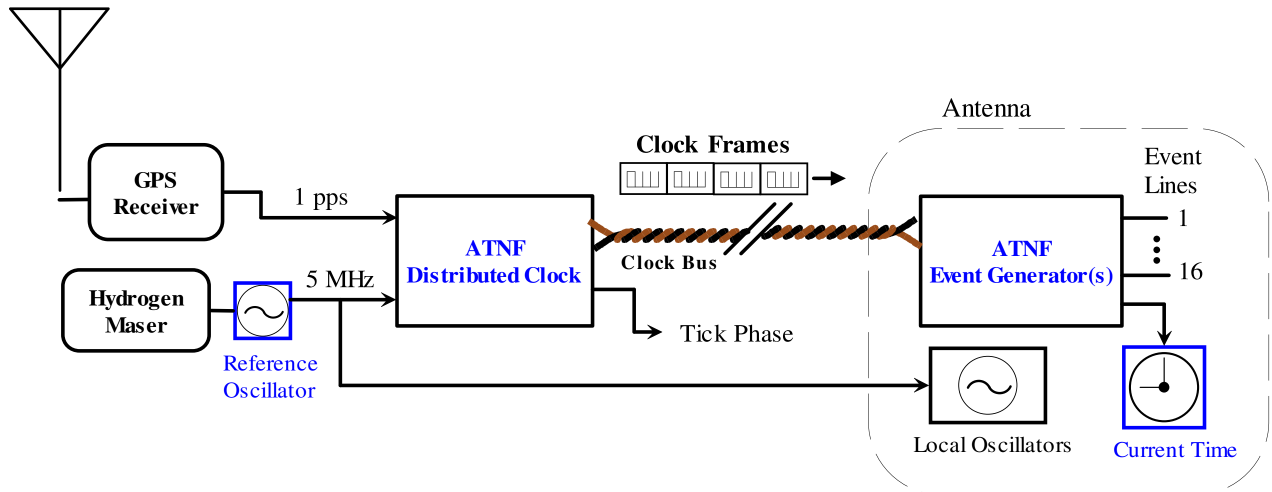

Figure 3: Basic architecture.

An 'ATNF Event Generator' (ATEG) receives and decodes the Clock Frame data. An ATEG can be pre-programmed to change the state of any of its sixteen digital output lines at an absolute time with microsecond precision [3]. Through software control it can generate pulse trains and single events with high precision and stability.

H-Maser / Reference Oscillator

There are one or more H-Masers at each observatory site. Parkes has a 'Smithsonian Astrophysical Observatory' (SAO) model VLG-10 on loan from the US Naval Observatory, while the ATCA and MRO use Russian made 'Vremya VCH-1005' H-Masers. Of the 10 or so SAO VLG-10s that were hand-made circa 1974, the one at Parkes has proven to be amongst the best in terms of long term stability. Long term timing stability is crucial for the pulsar timing observations conducted at Parkes, where pulse time-of-arrival (ToAs) for various pulsars is measured at intervals spanning years.

Variations in the thermal and magnetic environment affect the oscillation frequency of a maser cavity. In addition to their own thermal and magnetic isolation, our masers are housed in a temperature controlled room, away from the moving antenna structure. At Parkes, the temperature is maintained within a +/- 0.5 degree range.

Australia Telescope Distributed Clock

The original stand-alone version by designed Geoff Crapps[3] in the early 1980's to address the need to synchronise time between the soon-to-be-built ATCA and Parkes. The current hardware/firmware implementation is in the form of an extended Peripheral Component Interconnect (PCIe) card in a Linux host computer with kernel driver. Software utilities provide full control of the clock and retrieval of current earth and atomic time in various forms over the local area network.

The initial time need only be set to within 1 second. The clock then sets its internal counters to the correct microsecond count. Additionally, for fine adjustment, there is a facility to 'slide' the clock in 200 nanosecond steps, (1 cycle of the 5 MHz reference), to minimise the tick phase, i.e. the phase between the 1 pulse-per-second (1pps) of the external GPS signal and the clock's 1pps.

The ATDC transmits a binary sequence of time information, a clock frame every millisecond. Each clock frame consists of 55 x 16 bit words which are pulse width modulated or Manchester encoded onto a 1 MHz carrier. A clock frame includes Binary Atomic Time (BAT), Universal Coordinated Time (UTC), Universal Time (UT1), Local Mean Sidereal Time (LMST), Tick Phase as well as local time and the accumulated number of leap seconds added to UTC, (DUTC).

Binary Atomic Time is a 64 bit number representing the count of micro seconds since the epoch, MJD 0.0, i.e. 00:00hrs on Nov 17 1858. BAT is an approximation to International Atomic Time (IAT) [4], where

$$\mathrm{IAT} = \mathrm{BAT} + \mathrm{offset} + \mathrm{rate} * \Delta\mathrm{BAT}$$

Rate is the error in the frequency of the reference oscillator, offset is the tick phase. The change in tick phase is closely monitored over time and the maser cavity fine-tuned to keep rate close to zero. Since the tick phase is transmitted with each clock frame, IAT can be recovered from BAT by the receiving ATEG.

Both DUTC and daily time corrections for earth 'wobble', (DUT1), are published in the International Earth Rotation and Reference Systems Service Bulletin A (IERS-A). IERS-A corrections are downloaded once per week and applied automatically each day at midnight UTC.

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The Parkes Pulsar Timing Array project (PPTA) has measured the time-of-arrival (ToA) of numerous millisecond pulsars over many years and compared the results to the predicted ToA of each pulsar [5]. The difference, known as the pulsar timing residual, for four pulsars is reproduced in the graphs in App. A [6]. The timing residuals of generally less than +/- 2 microseconds over more than a decade as shown in the graphs are only achievable due to the high stability and end-to-end precision of the ATNF timing system.

Australia Telescope Event Generator

The ATEG is currently implemented either as a PCI card in a Linux host computer, or, in the case of ASKAP, entirely in firmware embedded in instrument sub-systems, e.g. the ASKAP Digital Receivers and Correlator. A kernel driver provides the low-level software interface for the PCI card, whereas the embedded version is controlled via Ethernet with commands encoded in Universal Datagram Protocol (UDP) packets.

The main functions of an ATEG are to maintain accurate current time by 'grabbing' clock frames as they are transmitted via the clock bus and to generate timed digital events with microsecond precision at any of the sixteen digital output lines. Current BAT, UTC, LMST, etc. read from the latest clock frame are available to a host process. Additionally, interrupts can be pre-programmed to occur at any BAT, by assigning one of the output lines as a 'self-interrupt' line [7], thus allowing fine-grain timing control of software tasks and loops.

Internally, an ATEG stores event requests as paired elements of BAT and output line states in a 256 element First-In-First-Out (FIFO) register. Higher level software supplies the FIFO with a sequence of required events ahead of time. Both simple and complex pulse trains can be generated continuously provided the number of output lines in use and the pulse width are such that the host process is able to refill the FIFO before it becomes empty.

The most recent implementation of a higher level software application for the ATEG is the Event/Timing control software (EVT) developed for ASKAP. ASKAP uses the Experimental Physics Industrial Control System (EPICS) framework for its instrument monitor and control software. The EVT is an EPICS Input / Output Controller (IOC) that provides a simple, parameter based interface to produce multiple, independently controlled waveforms and soft events for synchronising remote systems via EPICS Channel Access.

[2] In the early years of the LBA (circa 1990), compact, low-cost GPS receivers were not available. The Masers at Parkes and the ATCA were synchronised by monitoring an ABC TV transmission signal based on a Rubidium clock.

[3] Retired, CASS, Marsfield

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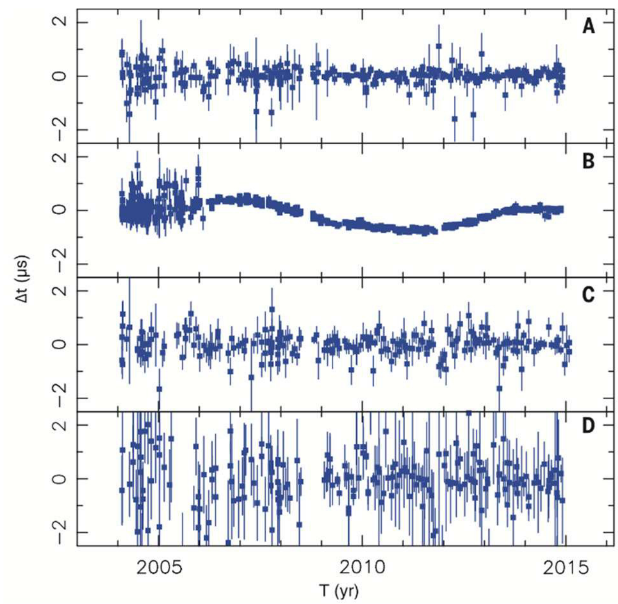
APPENDIX

App A: Residual pulse times of arrival, Δt, of four pulsars observed at Parkes since 2004 [4]



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[4] As published in [7]. Reproduced here with kind permission of Shannon R. (CASS, Marsfield)

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