Timing of Optical Pulsars with two high time resolution photometers at Asiago and NTT

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Abstract

We have built two single photon very high speed photometers (Aqueye for the Asiago 1.8m telescope and Iqueye for the 3.5m ESO NTT) as prototypes of a 'quantum' photometer for the European Extremely Large Telescope (E-ELT)

The two photometers are the most accurate 'time machines' available to optical astronomy. Under the control of a GPS receiver and a Rubidium clock, the arrival time of each detected photon is referenced to UTC with a precision better than 500 picoseconds, continuously for hours of data acquisition. Light curves for three optical pulsars (Crab, B0540-69, Vela) will be reported. Results from simultaneous observations of the Crab pulsar with the Jodrell Bank RadioTelescope will also be reported.

Introduction

High Time Resolution Astrophysics is the subject of many researches, both theoretical and observational, thanks to the advances in fast single-photon detectors which have the capability of accurate time tagging (see Shearer et al,. 2010). We have built and operated two single photon very high speed photometers (Aqueye for the Asiago 1.8m telescope and Iqueye for the 3.5m ESO NTT, see fig. 1, for details see Barbieri et al. 2010, Naletto et al. 2010, 2009) as prototypes of a 'quantum' photometer for the European Extremely Large Telescope (E-ELT).

The Photometers

Both photometers have an identical optical configuration: a pyramid splits the beam of light from the telescope into four beams, each feeding a Single Photon Avalanche Photodiode (SPADS) operated in Geiger mode. SPADs are read by a Time to Digital converter, under the control of an external Rubidium clock and GPS receiver, as detailed in the next Section. The two photometers are the most accurate 'time machines' available to optical astronomy. The time of arrival (ToA) of each detected photon is referenced to UTC with a precision better than 500 picoseconds, continuously for hours of data acquisition. The ToAs from the 4 SPADs are separately stored in the memory, and they can be binned at will according to the wanted S/N. Multicolor simultaneous photometry is also possible, thanks to 4 filter wheels in front of each SPAD.

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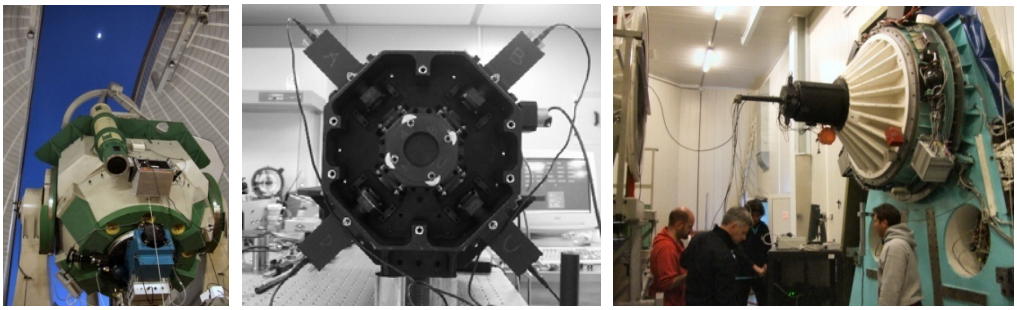

Fig. 1 – Left: Aqueye at the 182cm telescope.
Center: rear view of the instruments, with 4 SPADs fed by a pyramid.
Right: Iqueye at the Nasmyth B focus of the NTT.

The Time and Frequency Unit

The data acquisition system (see Fig. 2) collects the pulses from each SPAD, assign a very accurate absolute time tag to each event, and store the time tags in the external memory. This is not an easy task at all, because of the stringent requirements: namely, to produce an absolute, UTC referenced time tag for each detected photons with a rms accuracy of the order of 500 ps for at least one hour of continuous operation, coping with count rates ranging from few tens of Hz up to tens of MHz. Each of the 4 signals is transferred from the SPADs, by means of calibrated equal electrical length coaxial cables to ensure the same electrical delay, to one of the input channels of a time to digital converter (TDC) board. This TDC board is nominally able to time-tag the voltage pulses on its inputs with a 24.4 ps time resolution, obtained by means of a 40 MHz internal oscillator whose frequency is multiplied by 1024 by means of a phase locked loop (PLL) and a delay locked loop (DLL), providing a 40 GHz clock. However, the quality of the internal oscillator is insufficient to satisfy the extremely severe stability requirement of our applications, for which it is necessary to obtain simultaneously both the short-term stability typical of a quartz oscillator and the long-term one assured by a primary time reference. Therefore we selected a combination of a rubidium oscillator, a GPS receiver, and a post-processing algorithm. ITFU, based on the concept of correcting the long-term drift of the rubidium oscillator by means of a post-processing algorithm that uses the pulse-per-second (PPS) signal provided by GPS receiver. The GPS also provides the synchronization to UTC. The rubidium oscillator produces a 10 MHz sinusoidal signal, converted to a 40 MHz TTL signal by means of a frequency multiplication by a pulse generator and a signal generator. The 40 MHz TTL signal is inputted to the TDC board as its frequency standard, disabling the on-board clock.The rubidium oscillates in free-running mode, namely not disciplined by an external reference, because tests performed using a primary standard Caesium clock as reference, showed that this solution would worsen the phase noise. Furthermore, these tests showed that the rubidium accumulates a phase drift of approximately 65 ns after one hour, and 160 ns after two hours.

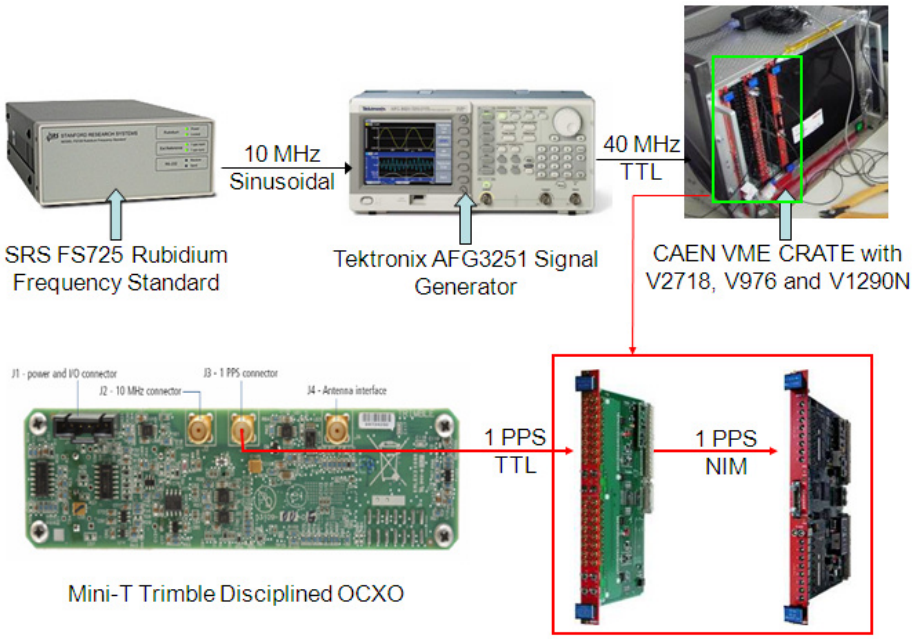

Fig. 2 – The Data Acquisition System and Time and Frequency Unit

By removing such drift, only a residual stochastic phase error remains, whose rms value is lower than 50 ps for a duration of more than 1000 s. The Allan variance has a minimum corresponding to 2.5×10^{-13} after 10^4 s. By adding the rms time errors in the SPADs (35 ps), those in the electronics chain (50 ps), and the residual phase errors (50 ps for one hour of observation) to the internal sampling discretization (24.4 ps), a total rms time error of approximately 100 ps is obtained, which satisfies the design requirements. This is the level of *relative* rms time accuracy that ITFU insures for one-hour long observations.

Results

The two photometers have had already several runs at both telescopes, acquiring a wealth of data on different rapidly varying objects. Fig. 3 shows the light curves of three optical pulsars, Crab (Zampieri et al., 2011 and in preparation), B0540-69 (Gradari et al. 2011), Vela (Naletto et al 2011).

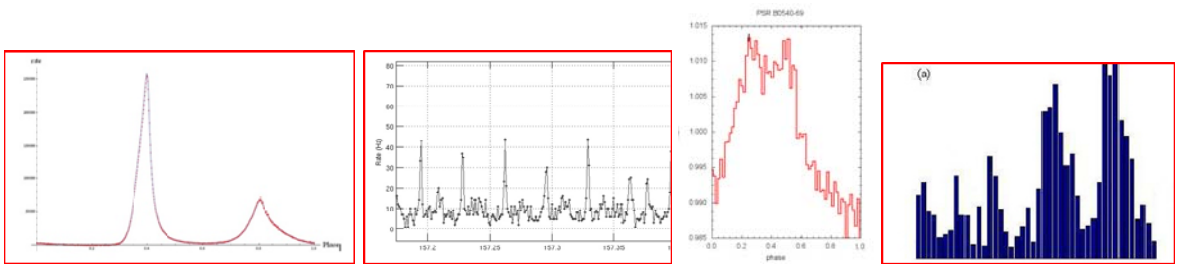

Fig. 2 – from left to right: light curve of the Crab pulsar with Aqueye, 10 min acquisition time, ToA binned at 1 ms; single pulses of the Crab pulsar at the NTT, data binned at 0.1 ms, light curves of B0540-69 and Vela at the NTT, with 3600 and 10800 seconds of acquisition respectively.

Moreover, in December 209, several data were acquired simultaneously with Iqueye at the NTT and the radio telescope of Jodrell Bank (JB). During these common observations, many giant radio bursts were recorded at JB; the correlation with the optical pulses (see Fig. 2, second panel) is now under investigation.

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