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SiFAP: A New Fast Astronomical Photometer

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Abstract

A fast photometer based on SiPM technology was developed and tested at the University of Rome "La Sapienza" and at the Bologna Observatory. In this paper we present the improvements applied to our instrument, concerning new cooled sensors, a new version of the electronics and an upgraded control timing software.

Keywords: instrumentation: photometer - stars: pulsars.

1 Instrument Description

The general description of our 3-channel photometer SiFAP (Silicon Fast Astronomical Photometer) is presented in Meddi et al. (2011; 2012). We only remind here that each channel is dedicated to a different target: variable source (channel 0), nearby sky (channel 1) and reference star (channel 2). A GPS receiver sends a Pulse Per Second (PPS) to a micro Processor (μP) which in turn produces a signal that we call Gated PPS. This last is used both to drive two LEDs in order to have an optical temporal marker and to synchronize our custom electronics.

During the last year we replaced the old Hamamatsu Multi Pixel Photon Counter (MPPC) modules with new ones, having the sensor cooled by a built-in Peltier cell [1]; we modified our electronics and to increase the uninterrupted acquisition time and to reduce the sampling gate duration from 0.55 ms down to 0.1 ms. The new block diagram of the instrument is shown in Figure 1.

The Thermo-Electric cooled system allows to reach a fixed working temperature of -10 °C, with a large reduction of the mean dark count. The S/N ratio is improved by a factor 3 with respect to the previous one. The modules have limited geometrical dimensions and low weight so they can be directly located at the exit pupil of the telescope. Other characteristics of the new sensors are similar to the old ones: pixel size of 50 μm for a total active area of 1 mm^2 and Photon Detection Efficiency with a maximum value of about 50% at wavelength of 440 nm[2].

The built-in electronics of each Hamamatsu module can generate three types of output: pulse count via USB interface already processed in time windows of 1 ms, analog and discriminated. We use the last one to feed our electronics which uses a new protocol for data exchange between a Field Programmable Gate Array and a μP and a new data storage support. The integration time windows for this output are now 0.1 ms. We called this electronics P3E, which stands for Pulsar Pulse Period Extractor.

The pointing and the signal maximization procedures and the fast pre-analysis to check the pulsating behavior of the pointed source are described in Meddi et al. (2012).

[1] http://www.hamamatsu.com/resources/pdf/ssd/c11208_series_kacc1176e03.pdf
[2] http://www.hamamatsu.com/resources/pdf/ssd/s11028_series_kapd1026e04.pdf

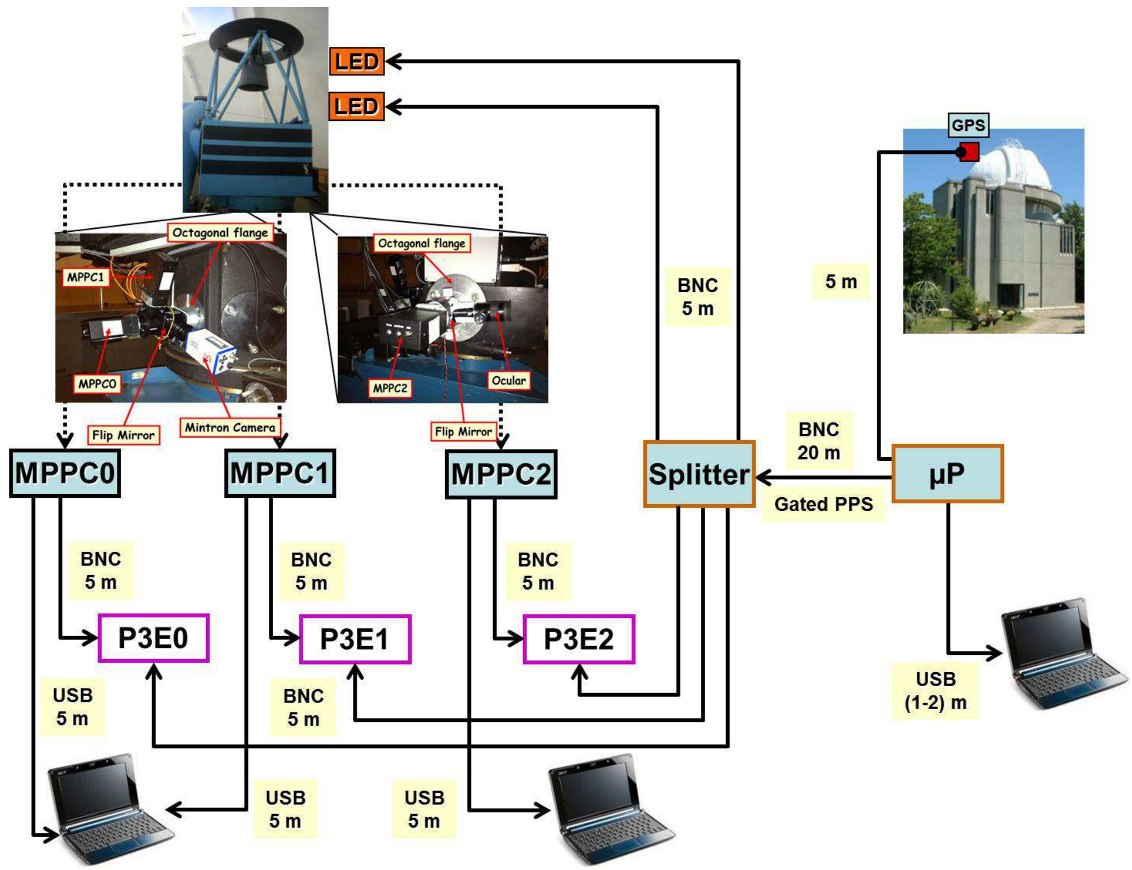

Figure 1: General block diagram of SiFAP mounted at the telescope. The GPS antenna is located outside the dome. Hamamatsu MPPC sensors are integrated in their modules, P3E units are fed by the discriminated output. Each couple of MPPC sensor and P3E unit is dedicated to a different target: variable source (MPPC0 and P3E0), nearby sky (MPPC1 and P3E1) and a reference star (MPPC2 and P3E2).

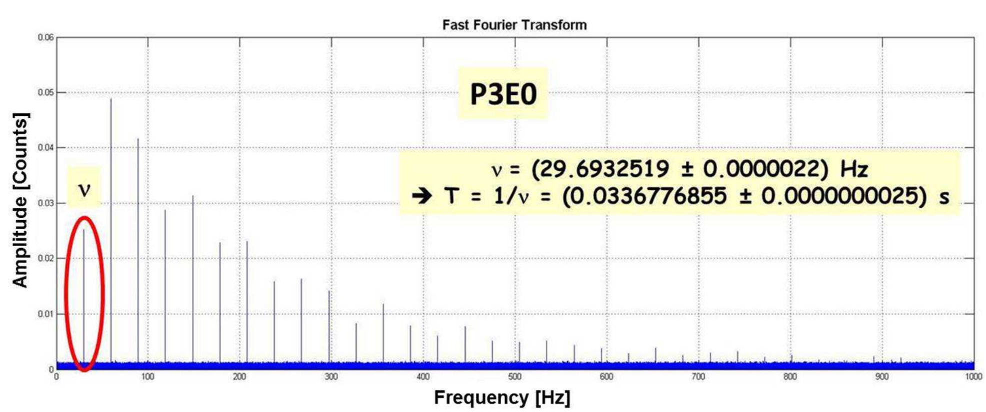

Figure 2: FFT applied to the whole raw data acquired by P3E0 on 2012, December 19.

	MPPC0 @ 1000 μs 2012, December 19 UTC 20:42:45.884	**P3E0 @ 100 μs 2012, December 19 UTC 20:42:45.885**
Xronos "barycentered"	ν = (29.693342 ± 0.000023) Hz T = (0.033677583 ± 0.000000023) s	ν = (29.693479 ± 0.000022) Hz T = (0.033677428 ± 0.000000022) s
J.B.O.	ν = (29.693664 ± 0.000010) Hz T = (0.033677218 ± 0.000000010) s	

Figure 3: Fundamental frequency and period values of the Crab pulsar signal obtained by our data with applied the heliocentric corrections compared with those computed from JBO ephemeris. The uncertainties on the JBO values are due to a numerical interpolation procedure. The quoted errors on our data are statistical only.

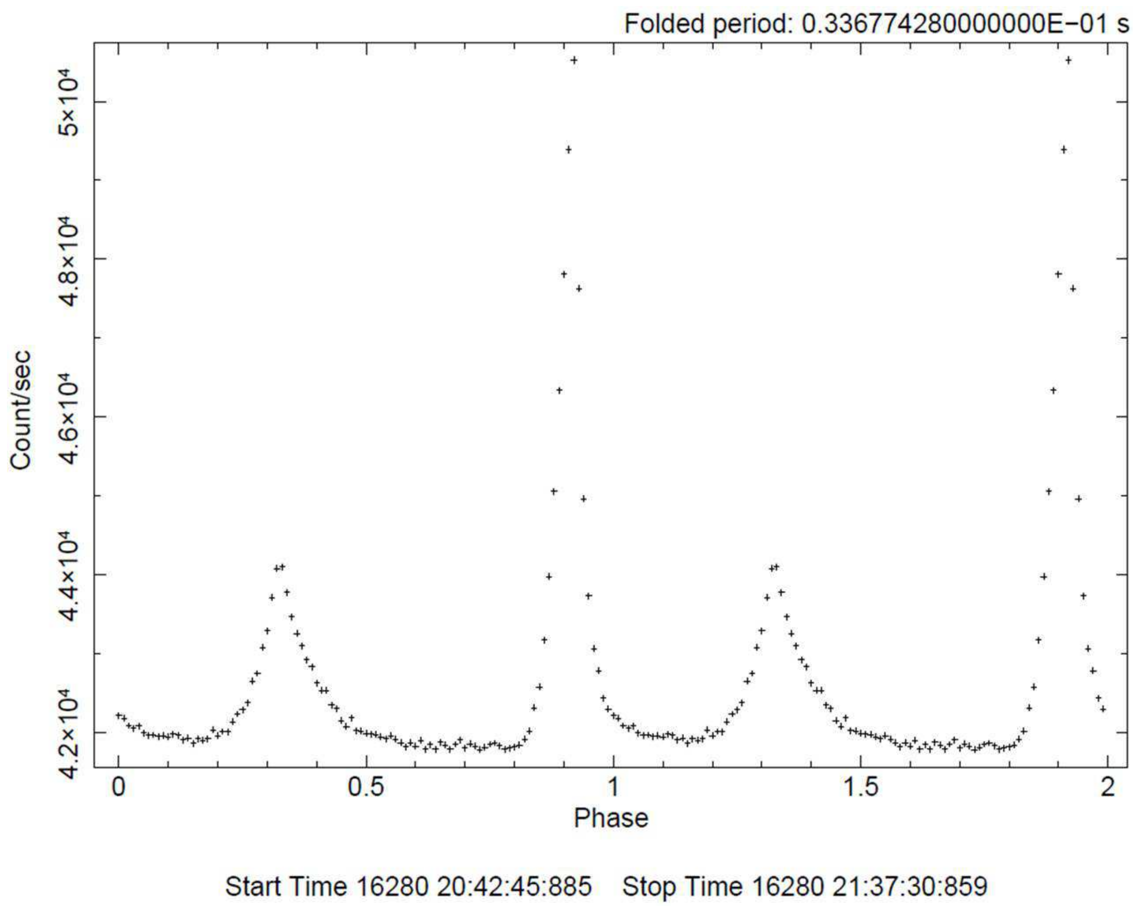

Figure 4: Crab pulsar light curve folded by the Xronos task efold for P3E0 (2012, December 19) corrected data.

2 Data Analysis and Results

On 2012 December 19 we observed the Crab pulsar with the Loiano telescope, for one hour. To optimize the pointing of the target, we performed a quick pre-processing analysis on a short acquisition of the data ($\sim 100\,$s), based on autocorrelation and FFT techniques. We then analyzed the whole data set with a FFT analysis to estimate the spin period of the pulsar. In Figure 2 we show the amplitude spectrum of the Crab pulsar signal obtained from data collected by P3E0. We used the Xronos package of the High Energy Astrophysics Science Archive Research Center (HEASARC) to apply the heliocentric correction (task *earth2sun*) and to determine the best fitting period for the Crab pulsar signal (task *efsearch*).

In Figure 3 we compare the Jodrell Bank Observatory (JBO) ephemeris[3] prediction for the fundamental frequency and period of the Crab pulsar signal with the estimates of the same quantities obtained by our barycentered data. The agreement between the two results is within 300 μHz for the fundamental frequency and 300 ns for the spin period. Such discrepancy can not be justified without taking into account systematic effects, which are explained in terms of the clock drift which depends on the temperature. This drift is estimated by measuring the time interval between the two optical markers generated by the Gated PPS signal, the first at the beginning and the second one at the end of the acquisition. Taking into account such effect, the differences for the spin period are reduced below 15 ns.

Systematic uncertainties are due to i) the propagation of the Gated PPS signal trough the cables and ii) the rising edge of LEDs. Such systematic uncertainties produce a total delay of about 320 ns. Finally, the accuracy on the pulse output time of the PPS signal which is $\pm$0.001 ms at the rising edge of the pulse itself. All these effects are not included in the numerical computation of the uncertainty on the period obtained by applying the barycentric correction.

The Crab light curves were obtained by using the task *efold* on the barycentered data; the result for P3E0 is shown in Figure 4. The shape of the primary and the second peak, and their flux ratio, are in good agreement with the literature data (e.g. Golden et al., 2000; Zampieri et al., 2011).

The sky and reference star measurements were processed in the same way as the ones belonging to the target to look for spurious signals which might interfere with the astronomical signal from the Crab nebula: no evidence of periodicity was detected.

3 Conclusions

We built a fast photometer able to collect data of periodic signals with high time accuracy integrating in time windows down to 0.1 ms. With the Loiano 1.5 m telescope we derived the period and a high S/N light curve of the Crab pulsar with a measurement duration of about 1 hour. In these conditions we obtained a fair agreement with the fundamental frequency and the spin period calculated from the JBO database.

We intend to upgrade our custom electronics aiming at reaching shorter time sampling keeping a good S/N ratio. Our final goal would be to compare fast optical measurements with the γ-ray, X-ray, IR and RADIO ones to explore more deeply the structure and the phenomena occurring in the emitting regions of pulsars. In particular, we want to study how the spin period slows down (dissipative process) and the amount of the eventual phase delay among the peaks in the various band (phase shifting process).

We need to collect high quality data with a 0.001 ms time windows to be able to perform these kind of investigations. To this purpose we modified our GPS system to reach a more accurate determination of the absolute time scale (within 100 ns) by using a burst of n Gated PPS signals instead of the single one presently used.

We started with theoretical computation of the minimum possible time sampling for a $V \sim 16$ mag object as a function of the telescope diameter. The results indicate that it could be possible to measure objects of the same magnitude as the Crab pulsar with similar S/N ratio in time windows shorter than 0.1 ms. For instance, with a 5 m telescope the integration time could be reduced down to 0.01 ms.

Moreover it is mandatory to have larger telescopes in order to have enough detectable photons and higher resolution on the absolute timing by adopting a military class GPS antenna which would be able to reach at least 1 ns accuracy.

In this case it would be necessary to upgrade the optical time marker by substituting standard LEDs with LASER ones.

[3] http://www.jb.man.ac.uk/pulsar/crab.html

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References

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DISCUSSION

B. ASCHENBACH: How do you explain that the second harmonic in the amplitude spectrum is higher than the first one?

F. AMBROSINO: The amplitude of the single harmonic depends on the shape of the light curve; In the case of the Crab pulsar in one period there are two emission peaks of different intensity and with a phase shift of about 0.45.