The Iqueye and Aqueye instruments: campaigns involving Asiago, TNG and other 4m class telescopes

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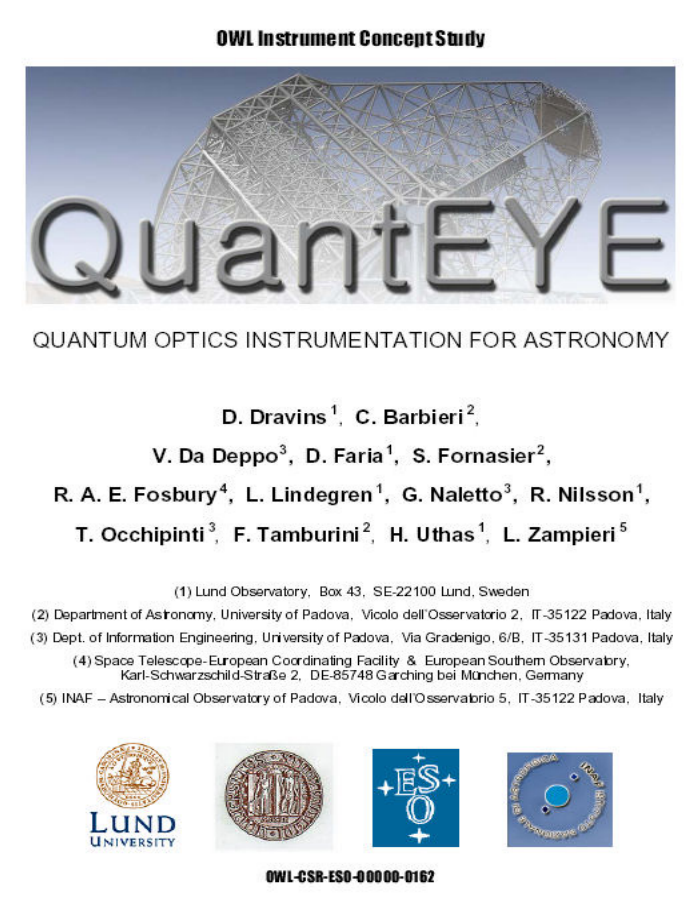
OWL Instrument Concept Study

QuantEYE

QUANTUM OPTICS INSTRUMENTATION FOR ASTRONOMY

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QuantEYE

In 2005, we completed the study of a novel instrument for the 100 m diameter Overwhelmingly Large (OWL) telescope
(QuantEYE, the ESO Quantum Eye; Dravins et al. 2005). The main objective was to demonstrate the possibility to **reach the picosecond time resolution (Heisenberg limit)** needed to bring quantum optics concepts into the astronomical domain.

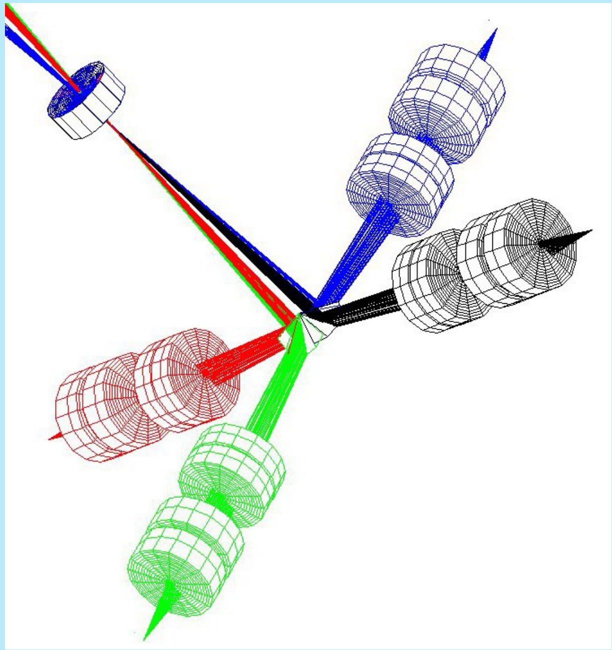
The study had two main scientific goals:

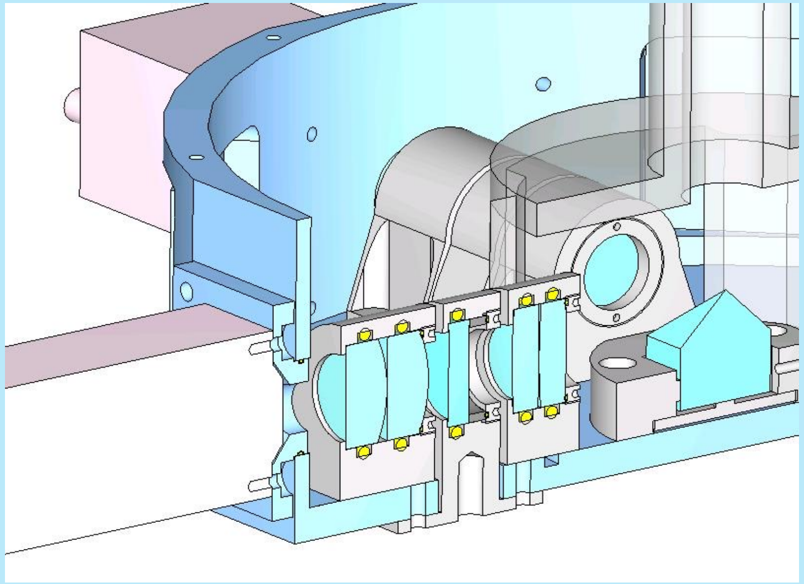
- To measure the ***entropy of light*** through the statistics of the photon arrival times.

- To perform optical ***High Time Resolution Astrophysics*** with unparalleled precision and accuracy.

Development of AQUEYE and IQUEYE

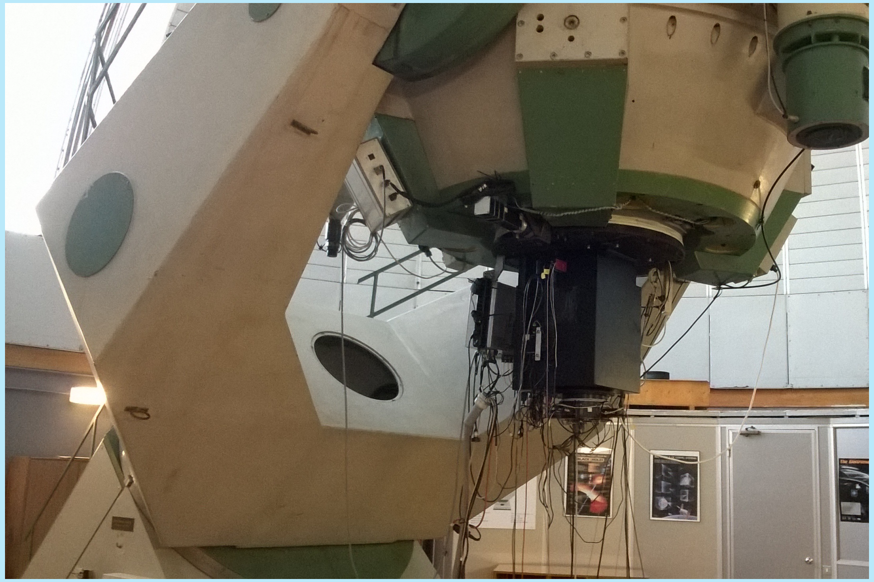
Starting from QuantEYE, we realized two similar downscaled prototypes, Aqueye and Iqueye. Both instruments adopted the concept of ***splitting the telescope entrance pupil*** in four parts, each of them focused on a Single Photon Avalanche Detector (SPAD) operated in Geiger mode.





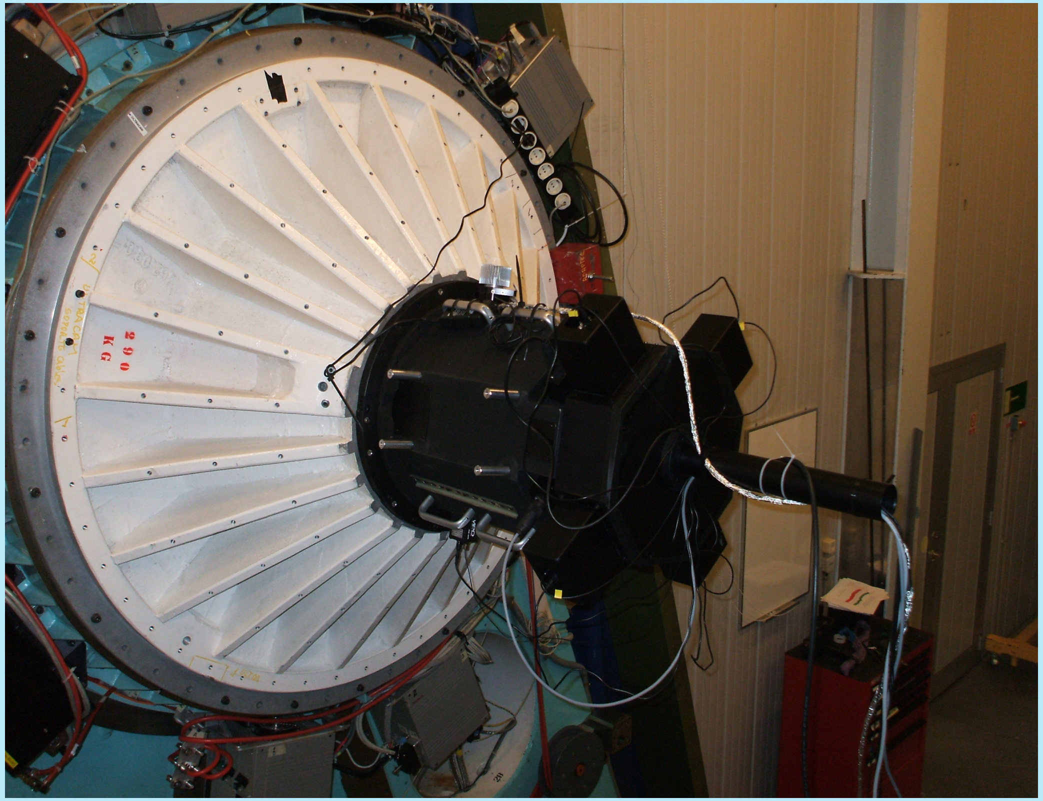
Both photometers are ***photon-counting non-imaging*** instruments, with a field of view of few arcsec, Filters can be inserted both in the primary beam before the pyramid and in each sub-beam, thus providing **multicolor simultaneous photometry**.

The two photometers



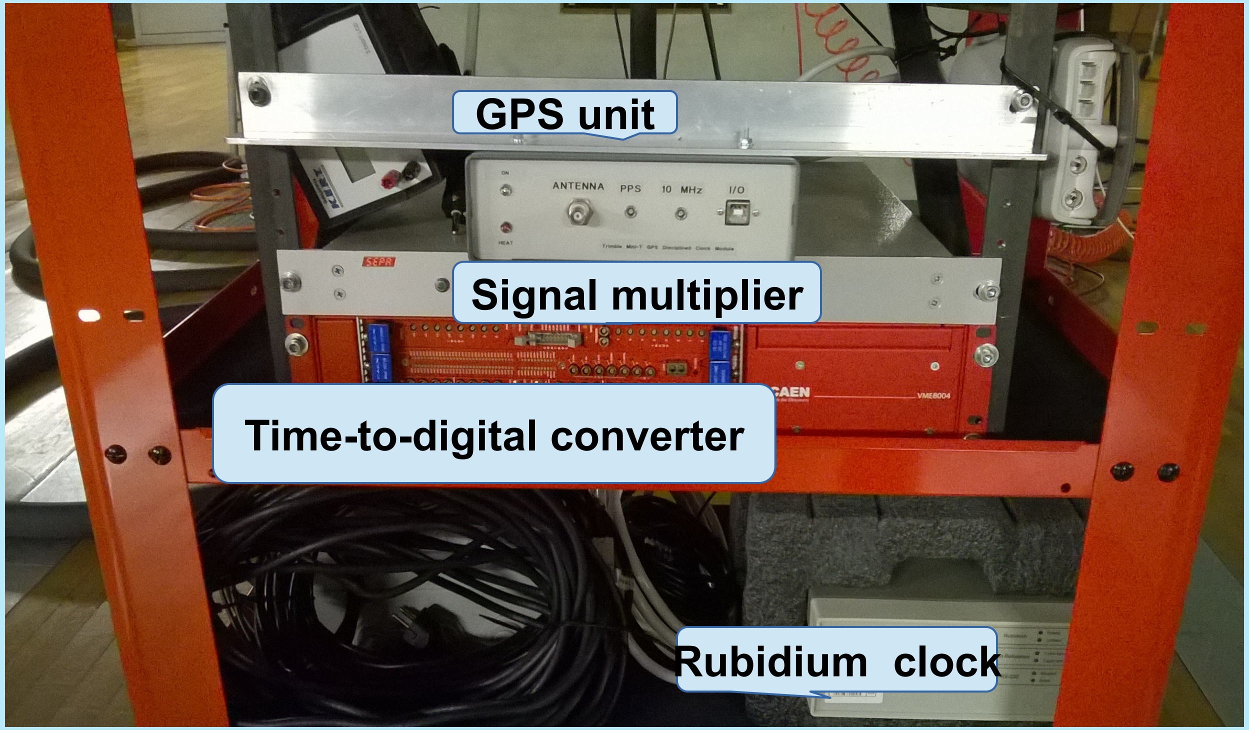
The first instrument was Aqueye (then upgraded to Aqueye+), mounted at the 1.8m Copernicus telescope in Asiago.

The second one was Iqueye. designed for 4m class telescopes, mounted at the 3.6m ESO NTT in La Silla in 2009 and 2010, and to the to the WHT and TNG.
Finally, today Iqueye is back in Asiago and fiber-optics coupled to the 122cm telescope.



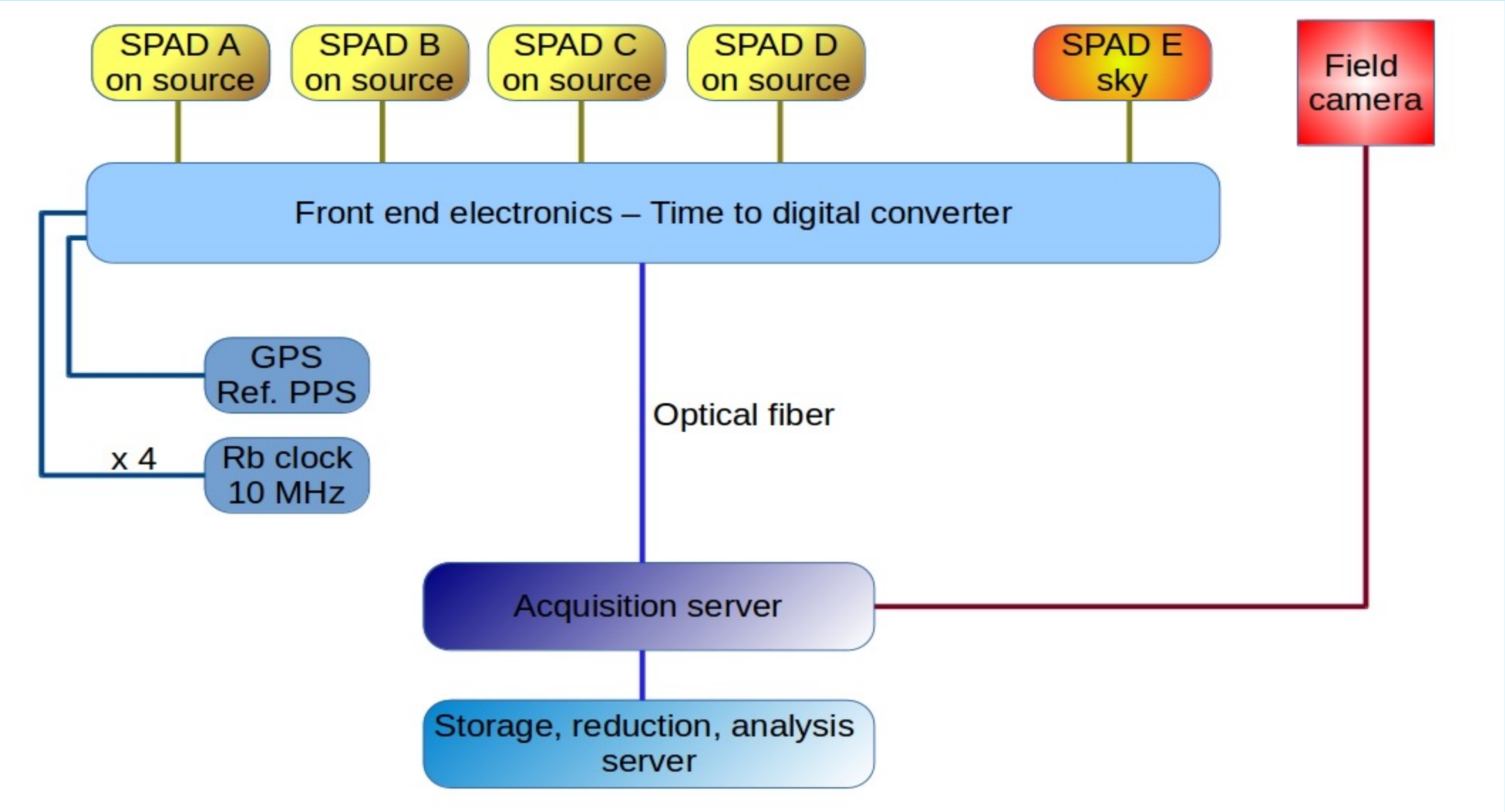
Detectors and Time Unit

Single Photon Avalanche Photodiodes *(SPADs)* with 100 μm pixel size, 35 ps time resolution, ~100 dark count rate, 6-8 MHz maximum count rate, quantum efficiency in the visible up to 60%.



The Time Unit tags the photon arrival times with sub-ns accuracy on a highly accurate time scale (UTC) provided by a Rubidium clock disciplined by a GPS unit.

The overall system



All time tags are stored in event lists that are analyzed in post-processing.

Post-processing is done with any convenient selection of time bin (from ns to minutes), thus providing a dynamic range of 6 orders of magnitude.

Scientific topics

The photometers have been used for studies on:

- *optical pulsars,*
- *lunar and asteroidal occultations*,
- *exo-planet transits,*
- *fast optical transients,*
- *searches for prompt/delayed optical flashes from Fast Radio Bursts*.

The observations are often carried out within the framework of ***multiwavelength campaigns***, in synergy with facilities operating from the Radio up to the Gamma-ray bands.

Some detailed results

Here, I'll present the results obtained on *four optical pulsars*. Optical pulsars indeed have been a most rewarding test bed for Aqueye and Iqueye. In particular the Crab Nebula pulsar has the advantage of being visible from Asiago, the Roque and La Silla.

Then, I'll show an example of a ***lunar occultation***.

At the end, I'll present the results obtained ***combining the arrival times from both telescopes***.

Optical pulsars

There are very few isolated radio pulsars pulsating also in optical wavelengths, and we have studied ***three of them*** with Aqueye and Iqueye:

1- the V = 16.5, 33 ms Crab Nebula pulsar

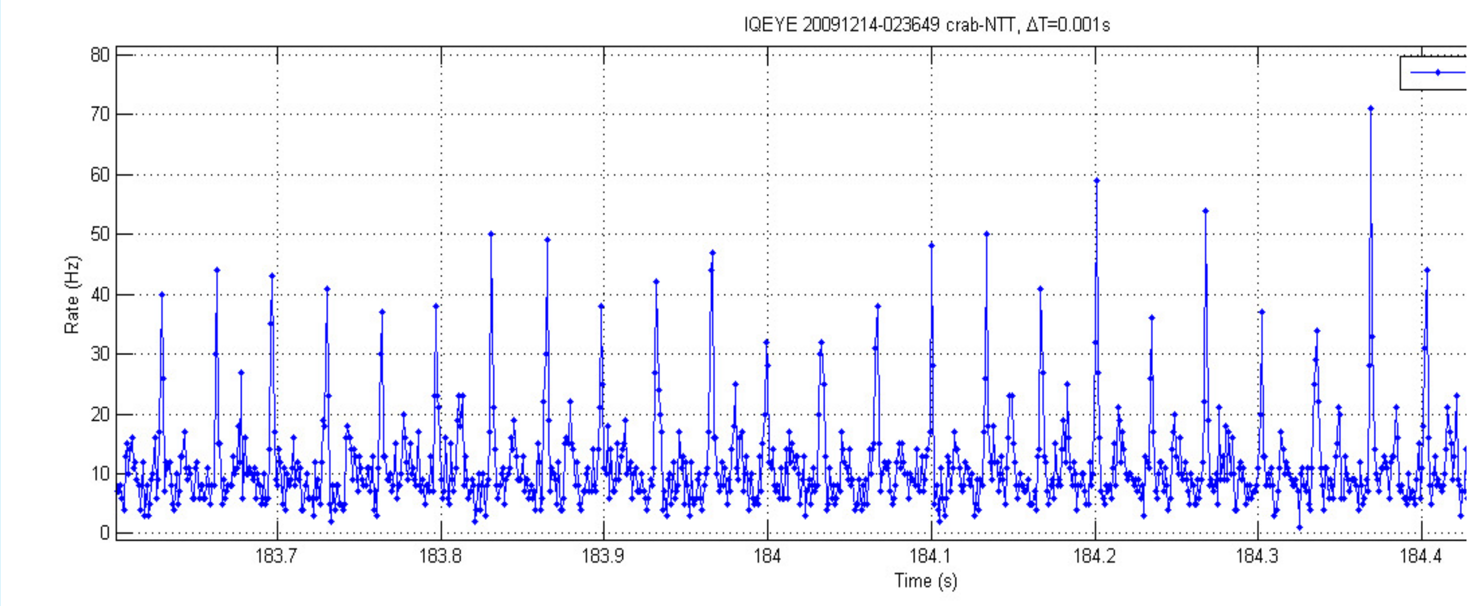
2 – the V=22.5, 50 ms pulsar in the Large Magellanic Cloud (designated as B0540-69), the only extragalactic optical pulsar known today

3 – the V=23.5, 89 ms Vela pulsar

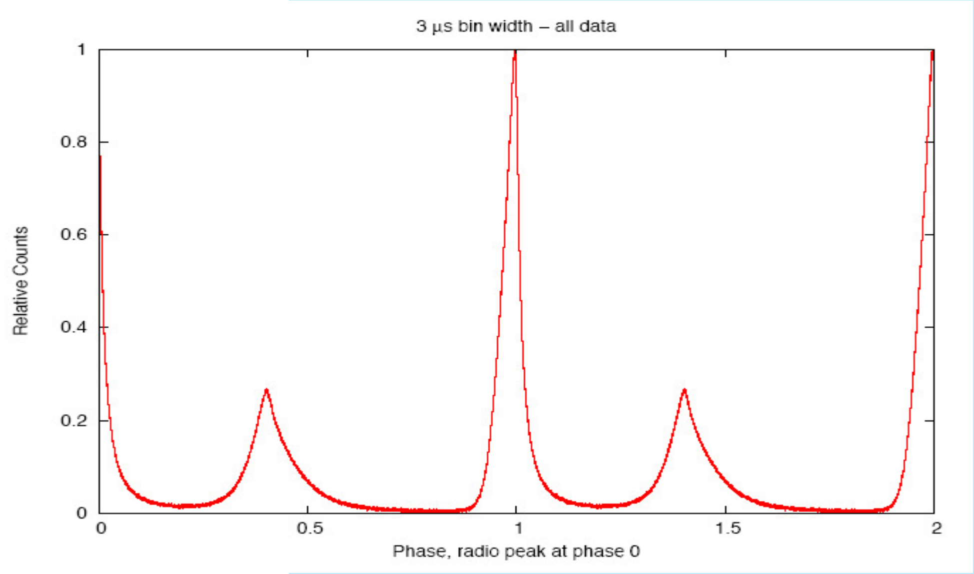
We also detected pulsations from the V= 15.6 J1023+0038 1 ms binary pulsar.

1 - The Crab pulsar

The Crab pulsar was observed at the NTT in January 2009 and again in December 2009.
In the last occasion simultaneous data were obtained with Jodrell Bank. The radio telescope detected hundreds of Giant Radio Pulses during the Iqueye observations.

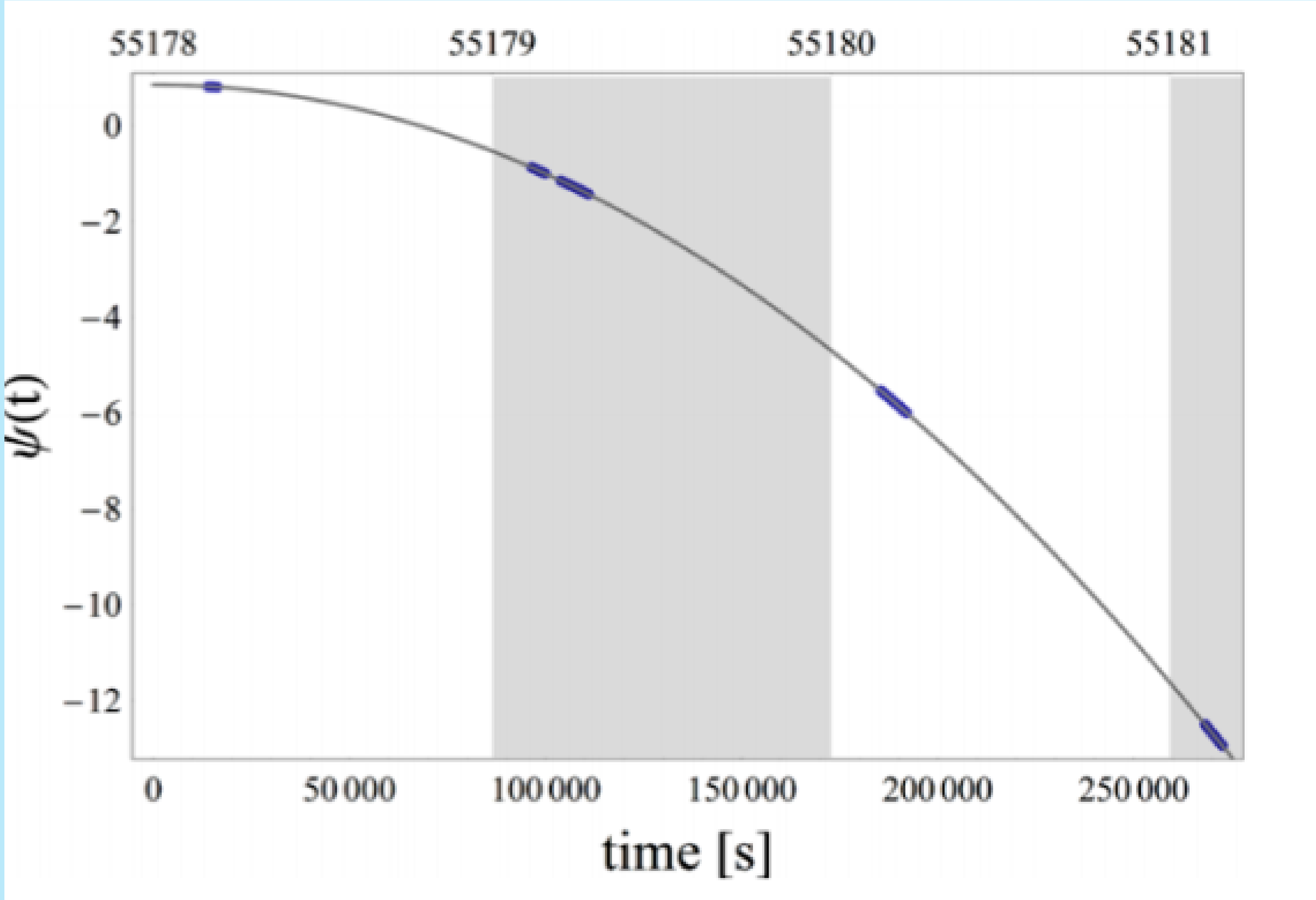


A series of individual pulses, raw data



data binned at 3 microseconds = 10^{-4} Period

Pulsar slowing down



Phase of the pulses with respect to uniform rotation. Time on top axis is in MJD. Few days of Iqueye observations provide a robust estimation of the pulsar slowing down.

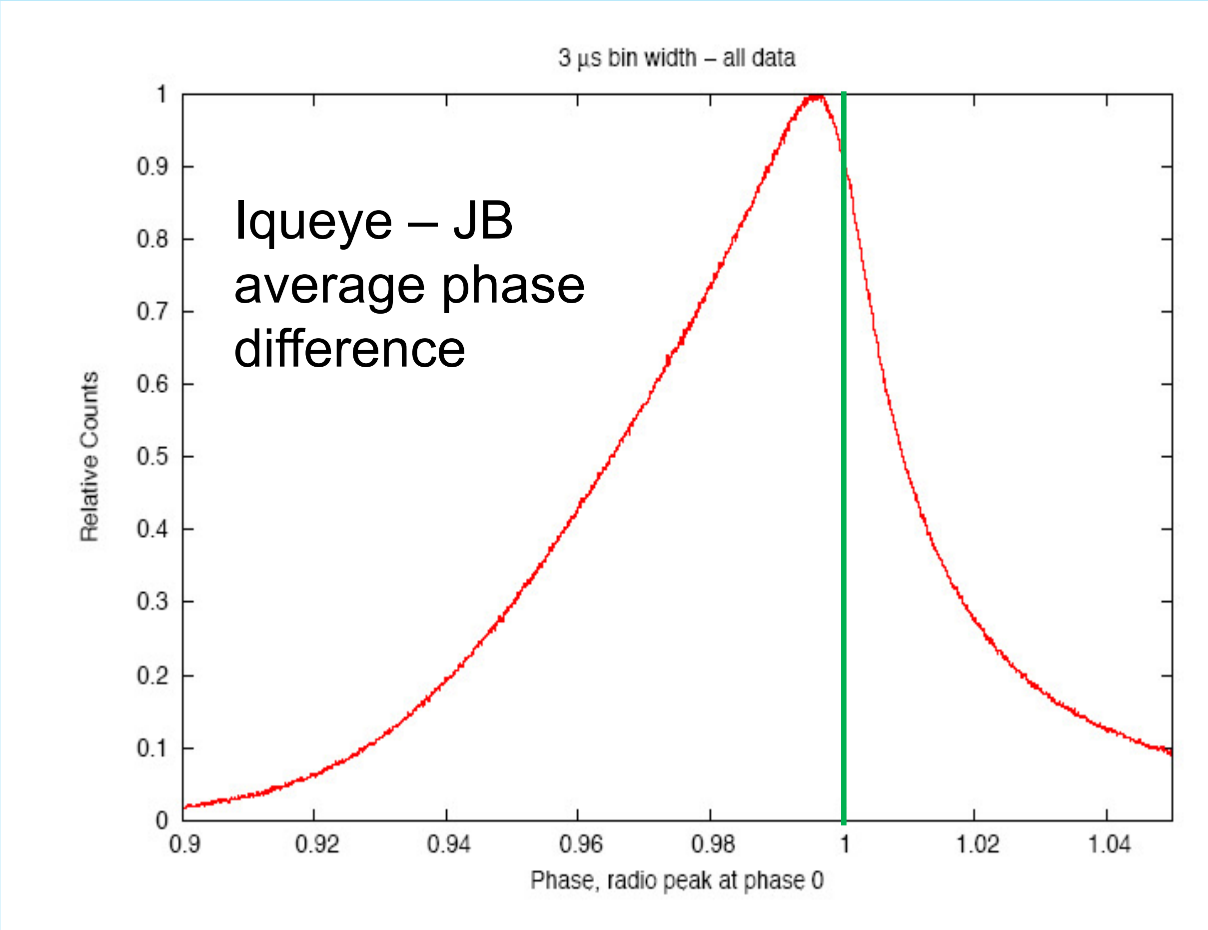
We derived a braking index

n = 2.44

similar to the radio one in the same period.
The age is consistent with the explosion of AD 1054.

Accuracy of period and phase difference with Jodrell Bank

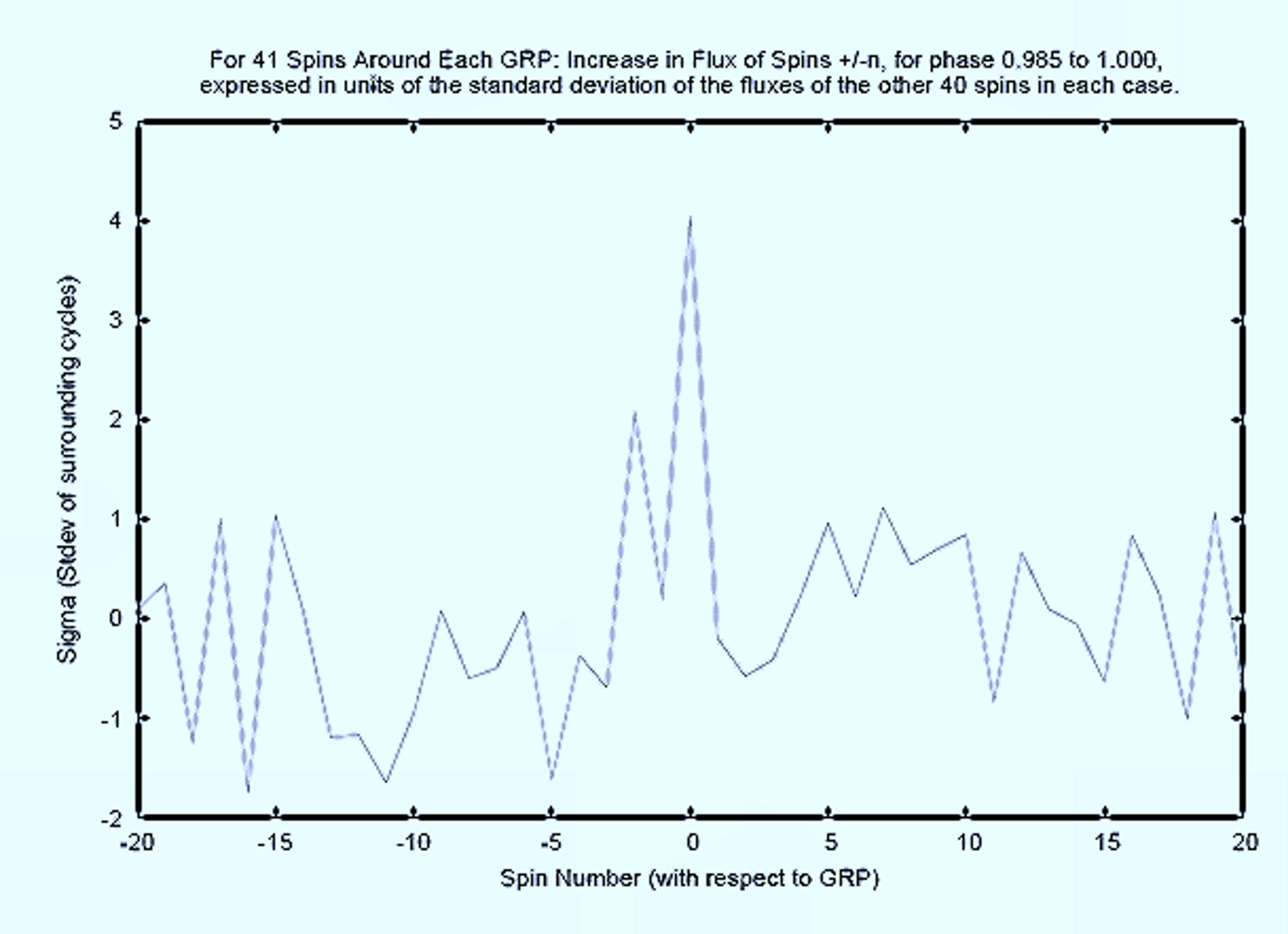
Iqueye and Jodrell Bank radio periods agree to the ***1 ps level.***



Iqueye data confirm the ***systematic optical-radio phase difference***, with the optical pulse preceding the radio one by about **200 microseconds**.

Optical signature of GRPs

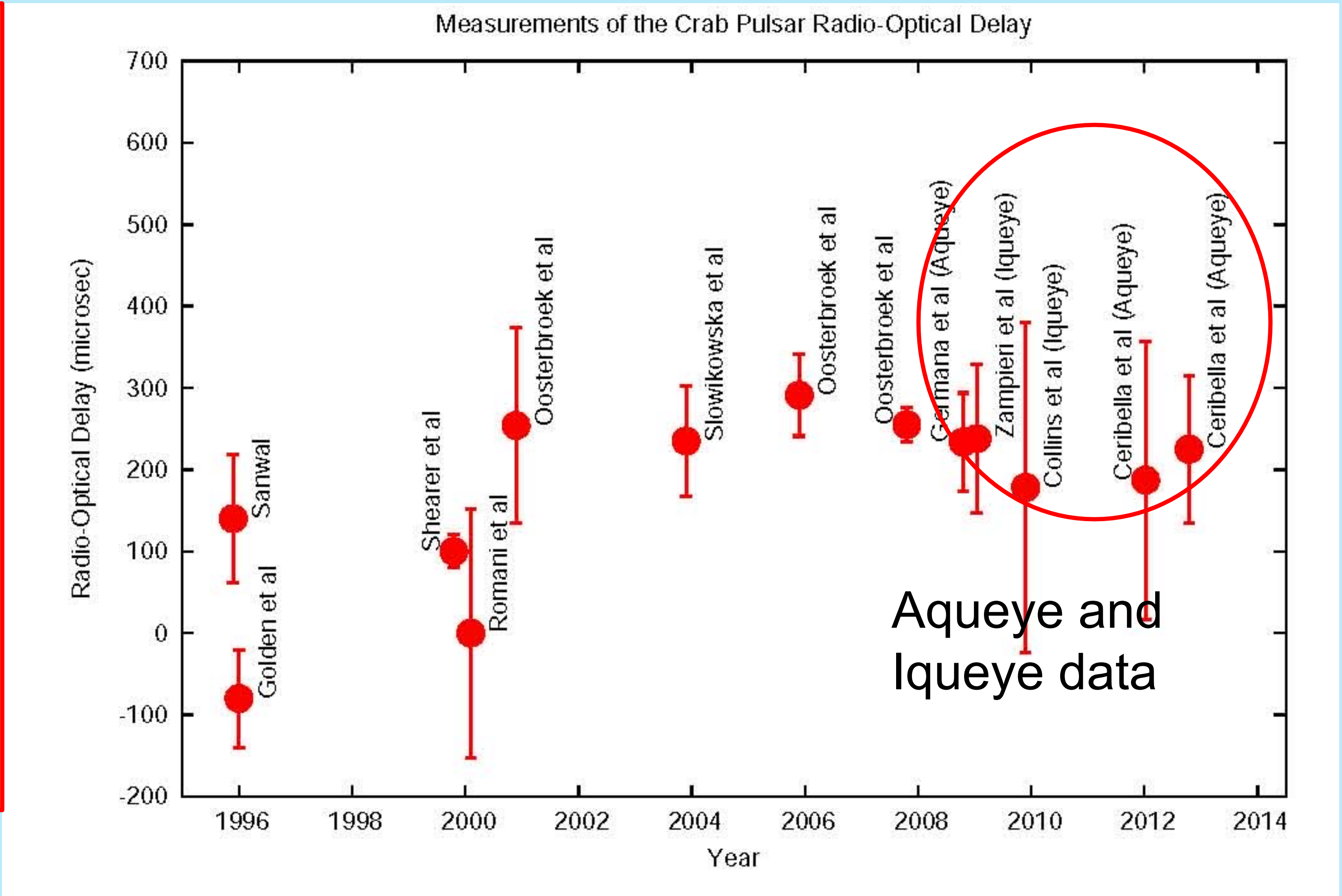
The night of Dec 14, 2009 Jodrell Bank detected 737 Giant Radio Pulses (GRPs) above a 6.0-σ cutoff, of which 663 had concurrent Iqueye observations.



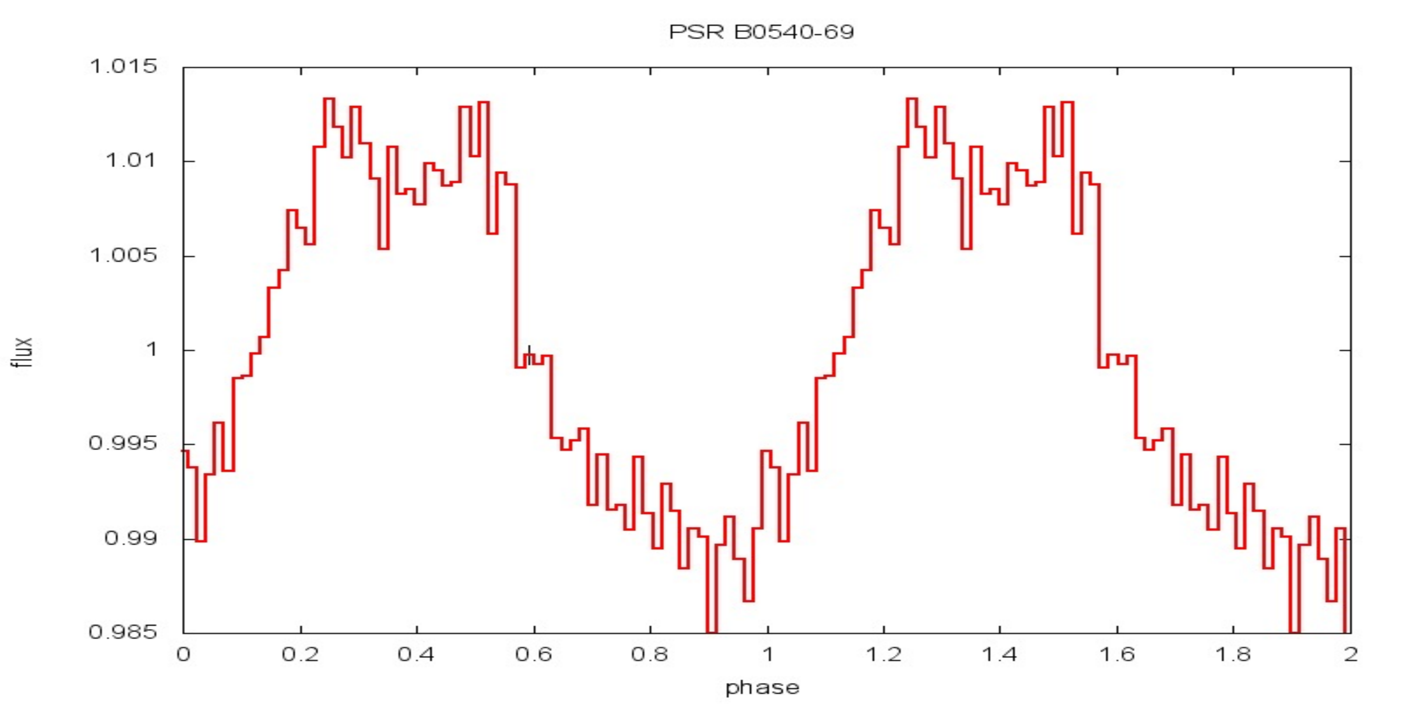
The Iqueye data confirm ***a noticeable increase in optical flux*** up to a 4-σ level in correspondence to the GRPs.

Values of the radio – optical delay of the main peak

The error bars in the Aqueye and Iqueye data is **dominated by the radio errors**.
Our interpretation of the delay is that optical and radio beams are misaligned by 1.5–3 deg because at the position where electrons emit optical photons the magnetic field has a slightly different orientation.
Regular monitoring observations carried out in Asiago do not find significant evolution of the delay.



The second brightest pulsar: B0540-69 in the Large Magellanic Cloud

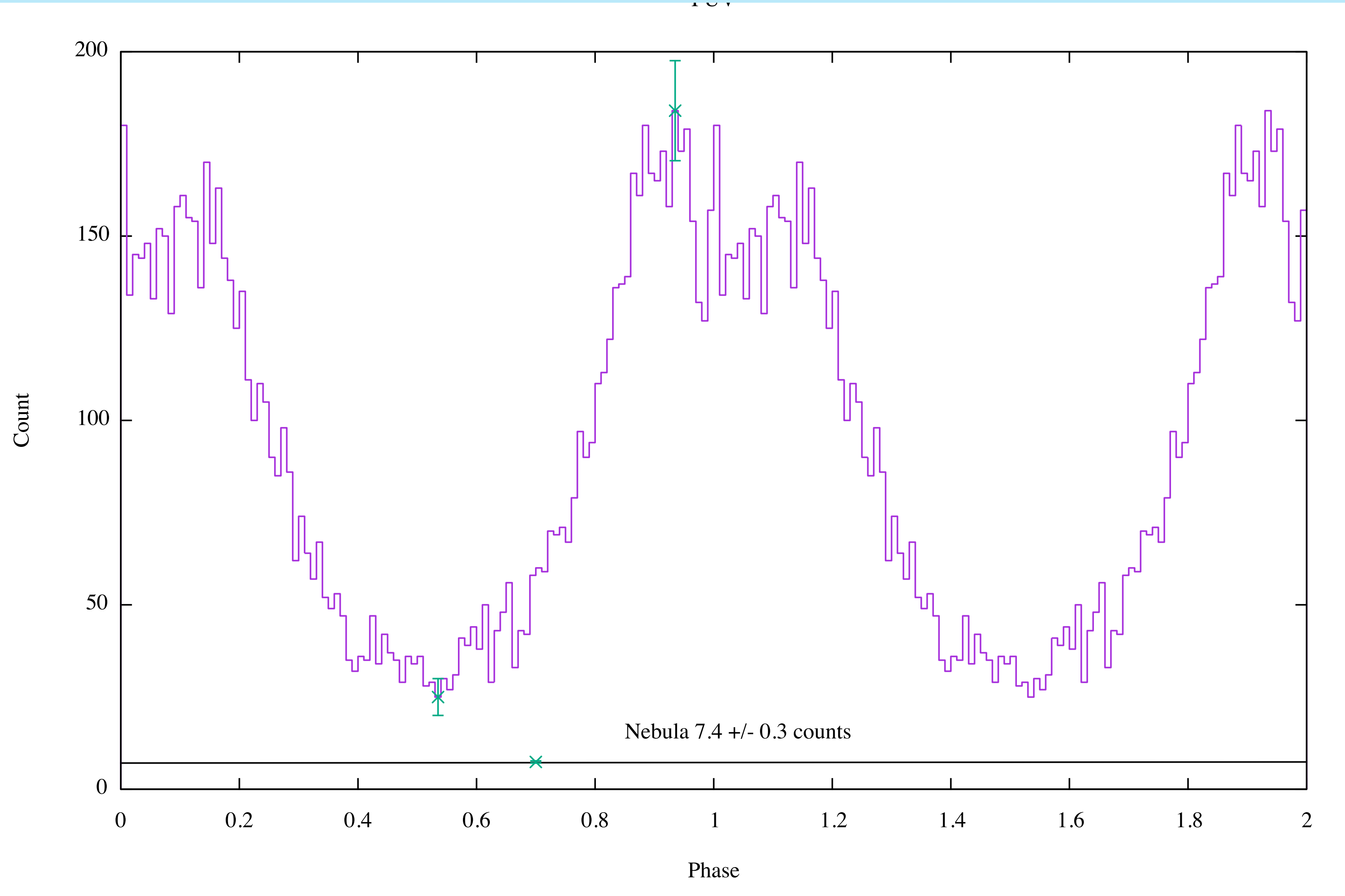


Two periods are shown for clarity. The double peak is statistically significant
This pulsar is approximately 100 times fainter than Crab's, therefore individual pulses could not be detected.

The braking index n (measurable only in optical and in X rays) over 27 years of optical observations is ***n* = 2.087 +/- 0.013**, decidedly lower than the magnetic dipole value.

Our observations extended by 9 years the time span over which optical data were obtained**.**

The UV light curve



In collaboration with Roberto Mignani. the pulsar was observed ***with the HST***, ***detecting pulsation also in the UV***.

B0540-69 is one of the 4 pulsars that are known to ***pulsate from the Radio to the Gamma-rays***.

The Fermi LAT detection and the Gamma to Radio light curves

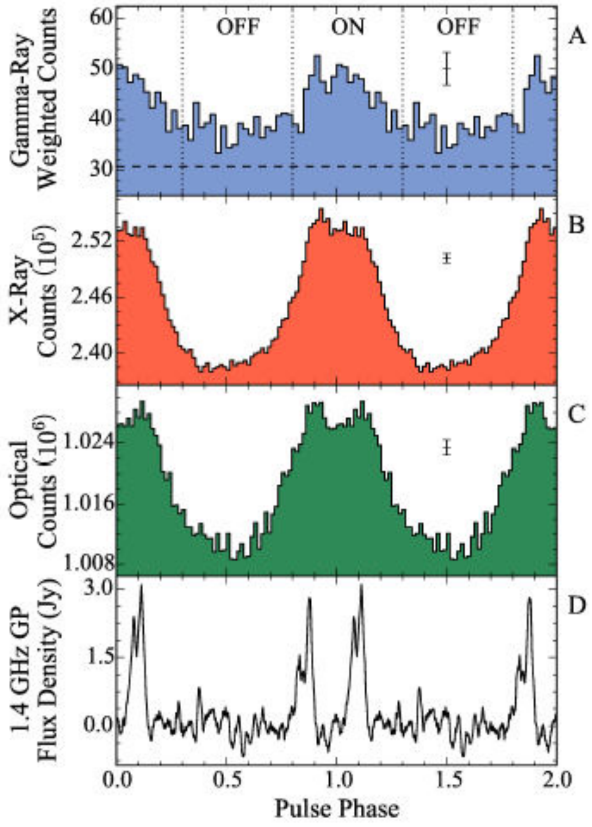
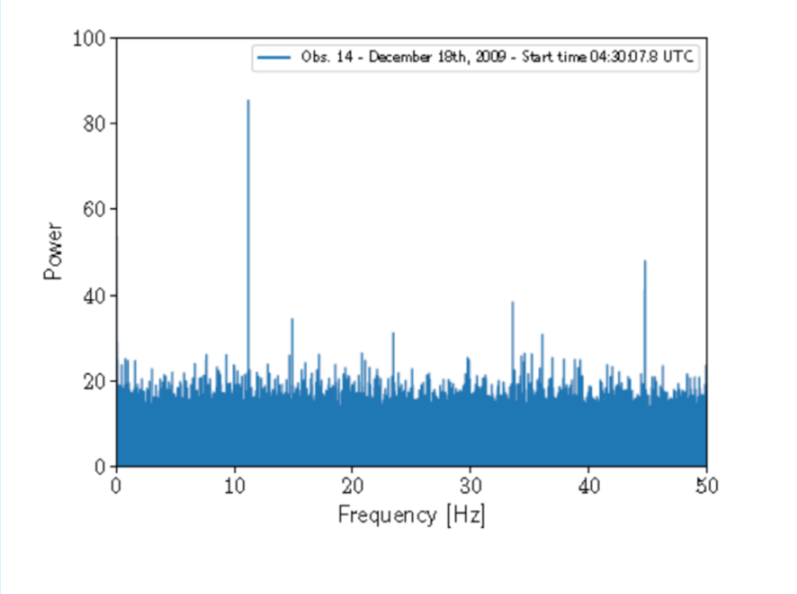


Figure 2: **Pulse profiles for PSR J0540−6919.** (A) Probability-weighted LAT count profile. The horizontal dashed line approximates the background level. Vertical lines indicate the on- and off-pulse regions used for the LAT spectral analysis. (B) RXTE X-ray integrated count profile. (C) NTT optical count profile. (D) Parkes radio flux profile from summing 18 bright giant radio pulses at 1.4 GHz. Two complete cycles are shown. The error bars in the top three panels represent the median phase bin errors.

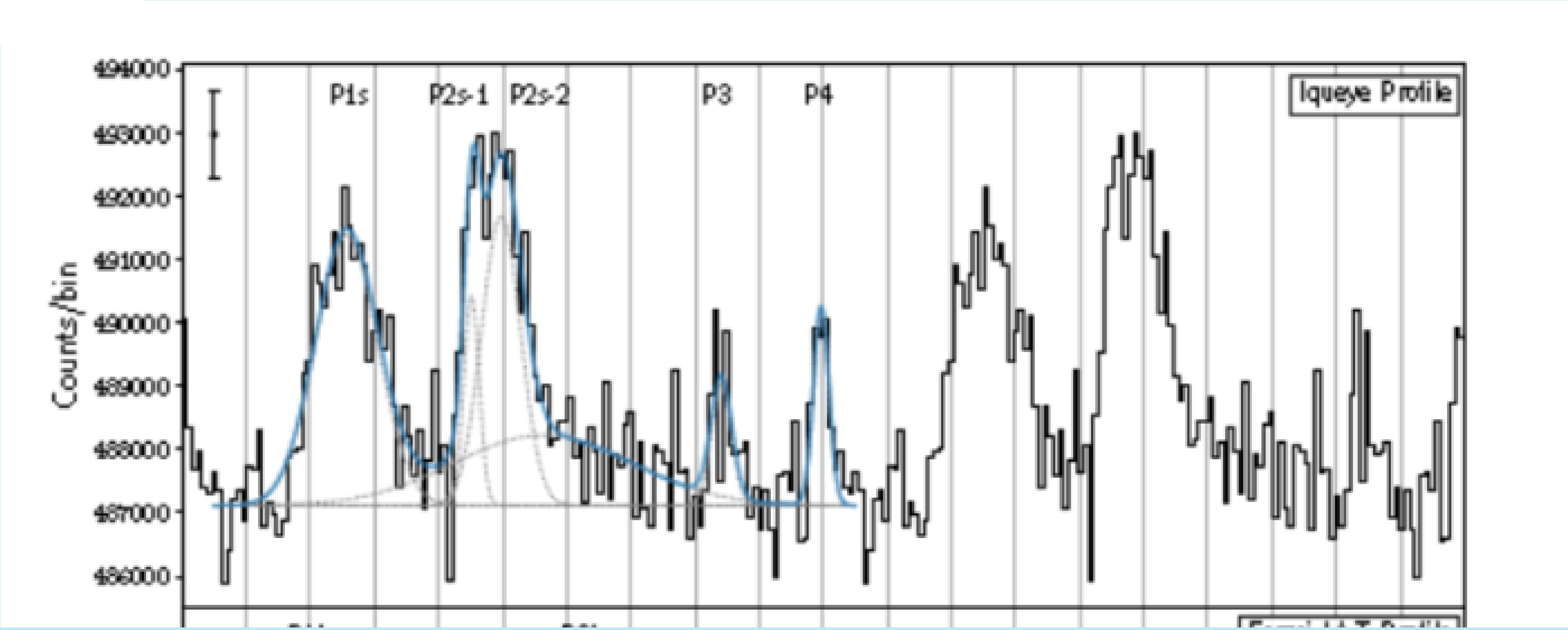
Iqueye



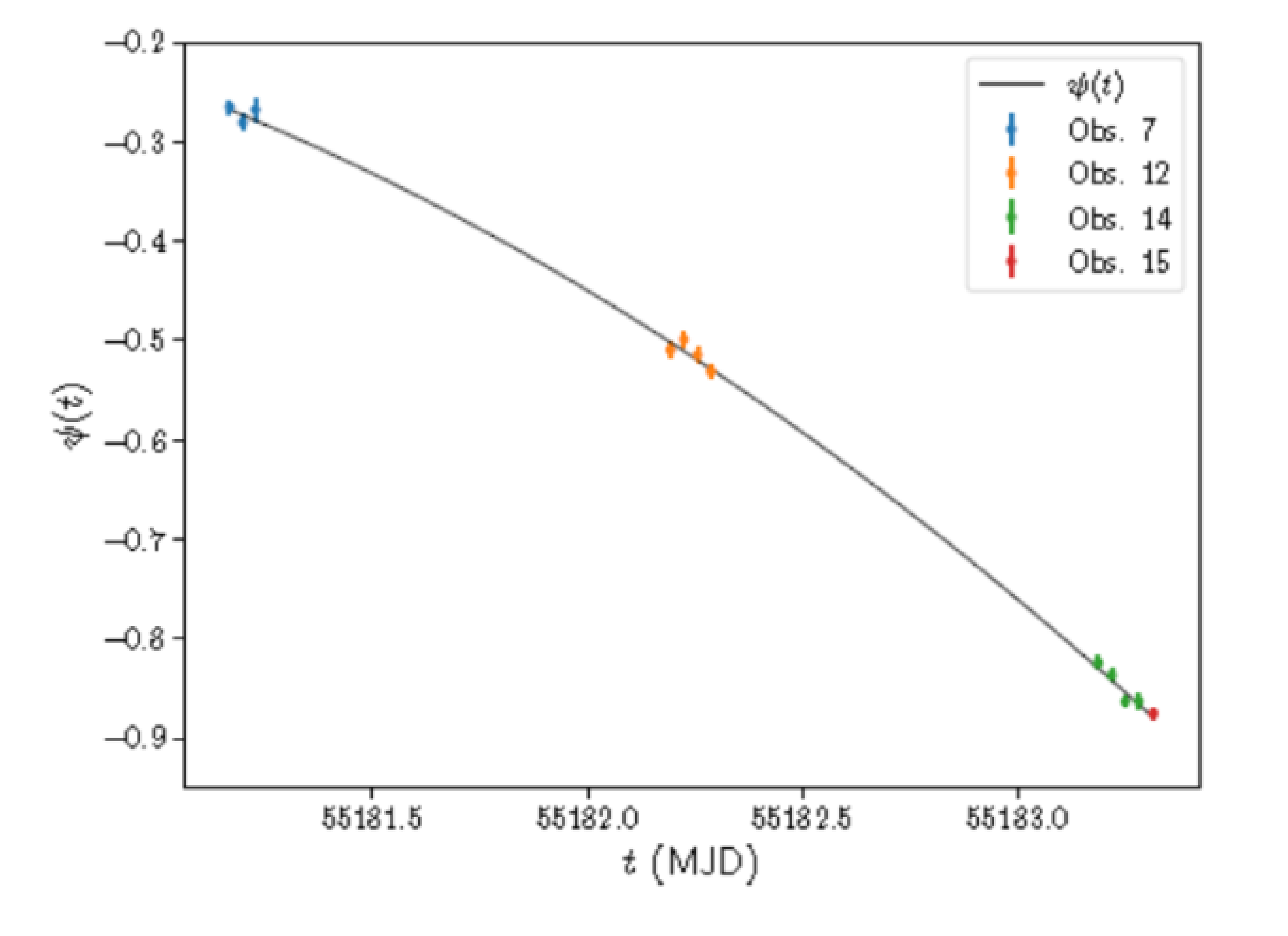
The faintest pulsar: Vela

The Vela’s pulsar is 10 times fainter than B0540-69. However, the periodic signal (period around 89 ms) is plainly evident from the Fourier transform of Iqueye data.

Two cycles are shown for clarity. The light curve is truly complex



Phase drift of the Vela pulsar

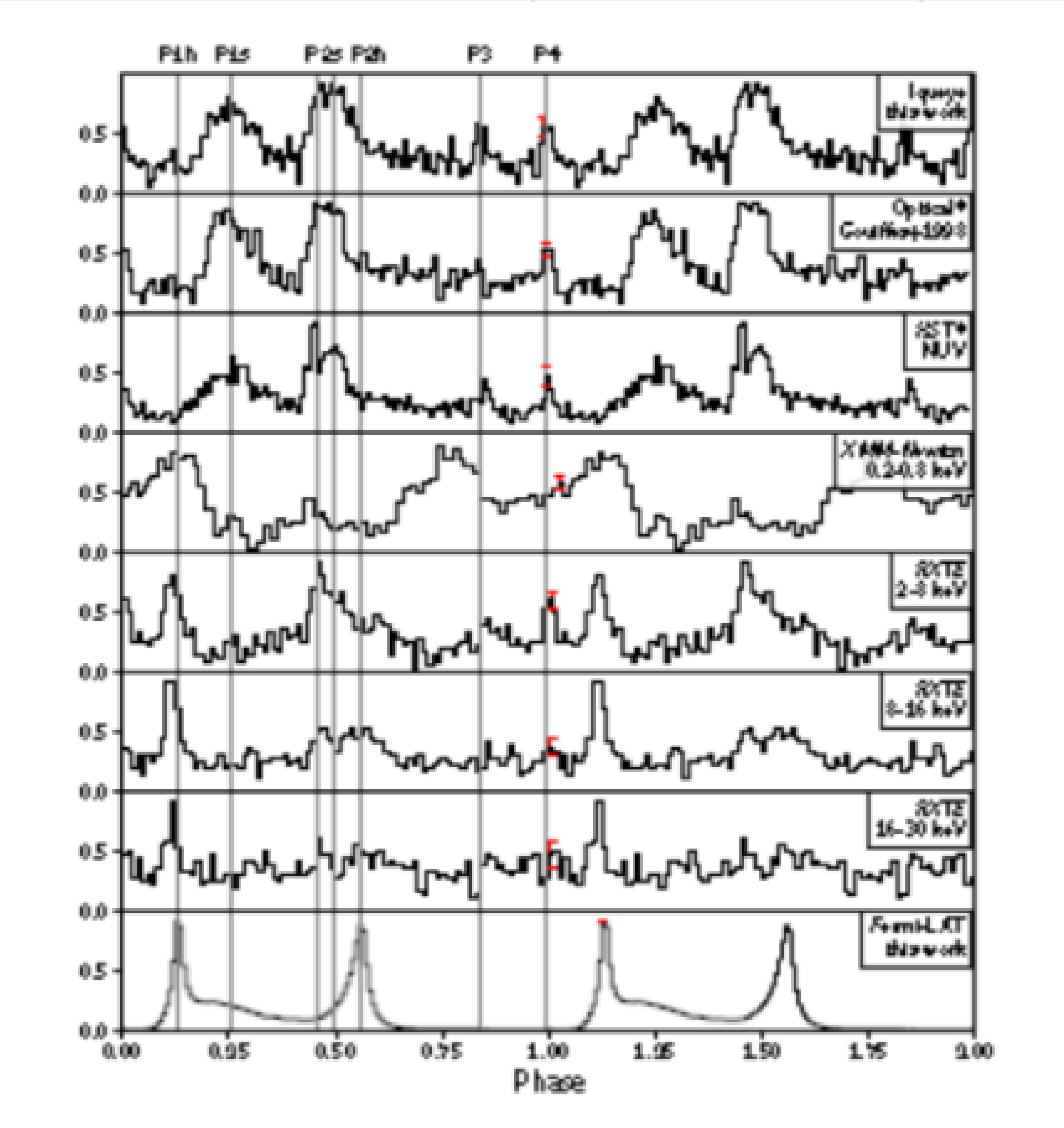


From our data alone we could not derive the braking index ***n***.

However, for the first time we determined the ***relative time of arrival of the Radio-optical-Gamma ray peaks*** with an accuracy of a fraction of a millisecond.

A mosaic of light curves at increasing energies.

The morphology of the light curves changes with increasing energies, different from Crab and B0540-69



Vela: a detailed Iqueye vs Fermi-LAT light curves

6 *Spolon et al.*

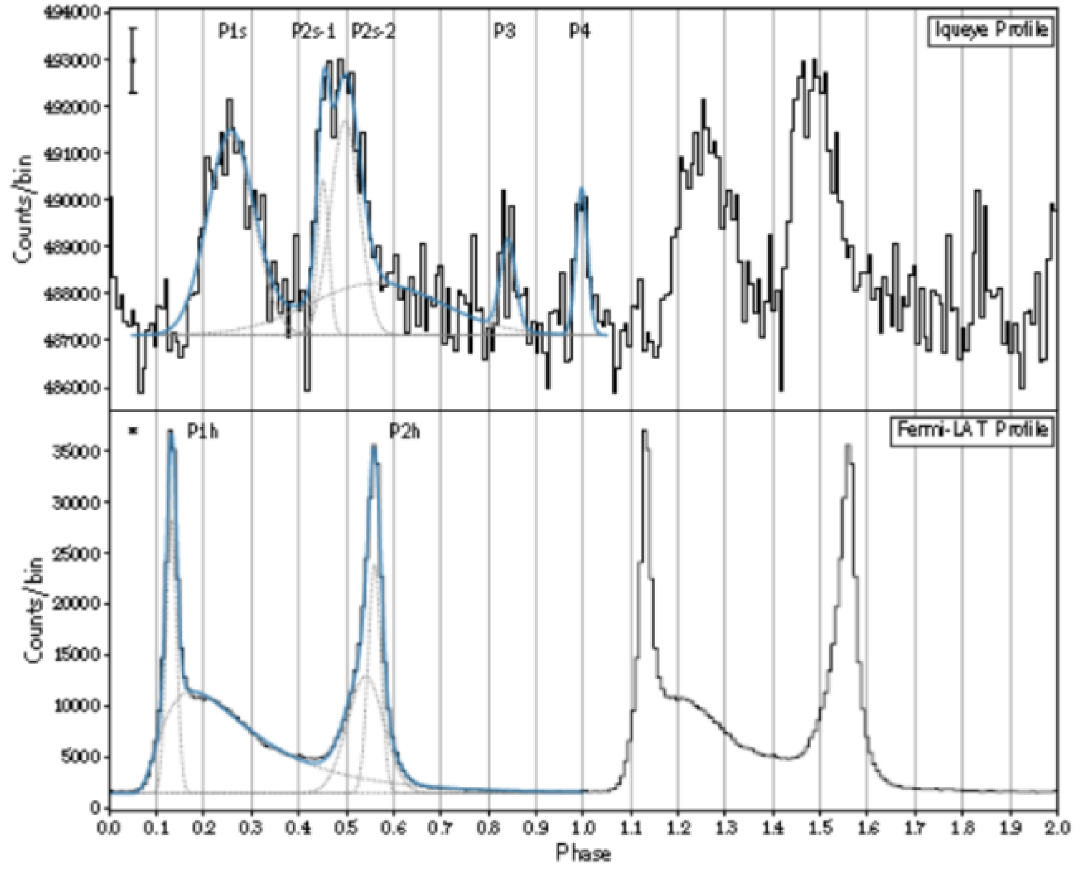
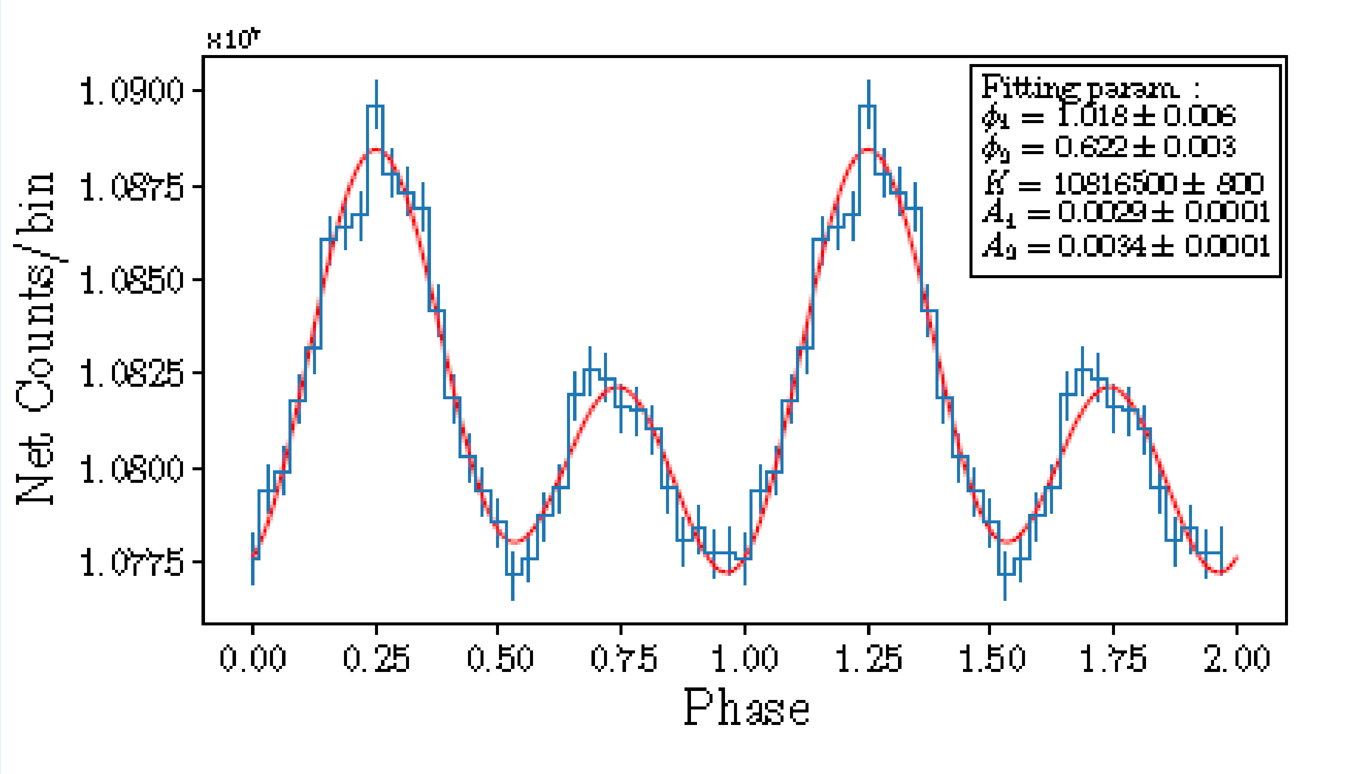


Figure 3. Two periods of the Vela pulsar pulse profile from the Iqueye optical observations taken in 2009 (*top panel*) and the *Fermi*-LAT gamma-ray observations taken during 3 yrs of its operation (MJD 54682.66–55793.85, *bottom panel*). The blue line in each plot shows the best-fitting analytical function which reproduces the profile. Individual components of these functions are also shown with gray dashed lines. Phase 0 corresponds to the radio peak. The average 1σ error bar is shown on the top left.

The millisecond PSR J1023+0038 with Aqueye



Initial period P_{init} = 1.687987440 ms

(in collaboration with Papitto and Ambrosino)

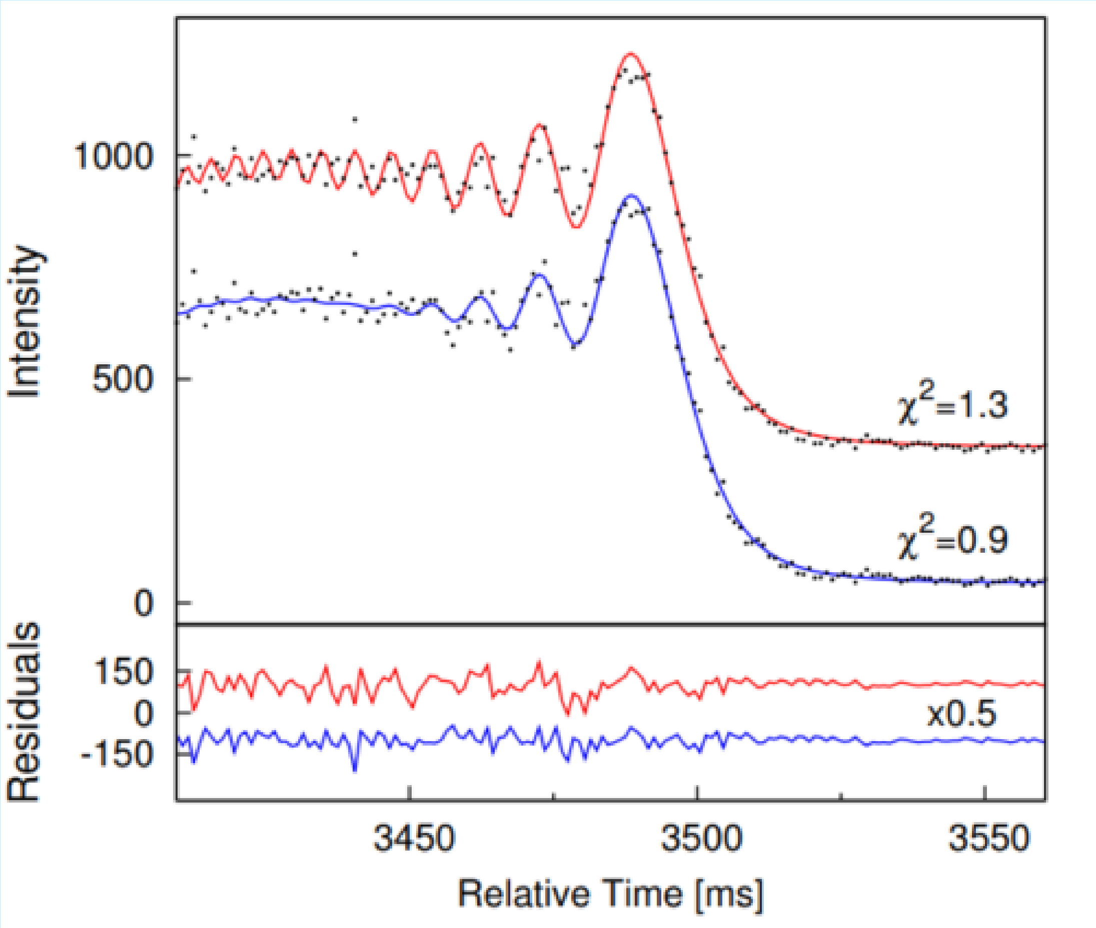
We made the first measurement of the timing solution and the frequency derivative of PSR J1023+0038 based entirely on optical data.

The spin-down rate of the pulsar is

$(-2.53 \pm 0.04) \times 10^{-15}$ Hz^2,

≈15-20% slower than that measured from the X-ray observations taken in 2013-2016 and 5-10% faster than that measured in the radio band during the rotation-powered state.

A lunar occultation with Aqueye



In collaboration with Andrea Richichi

Top panel: light curve (dots) for μ Psc (a K3-K4 giant)- The upper solid line is a fit with a point-like source, the lower solid line is the best fit with a uniform disk model. The best fitting value of the diameter is ***3.14 ± 0.05 mas***, namely ***34.2±1.2 solar radii***, using the GAIA parallax of 9.9 mas.

The reduced χ2 values for the two cases are also shown. The improvement of the fit is highly significant (Δχ2 > 30 for 1 additional degree of freedom).

Bottom panel: the residuals for the two fits, offset by arbitrary amounts and rescaled for clarity.

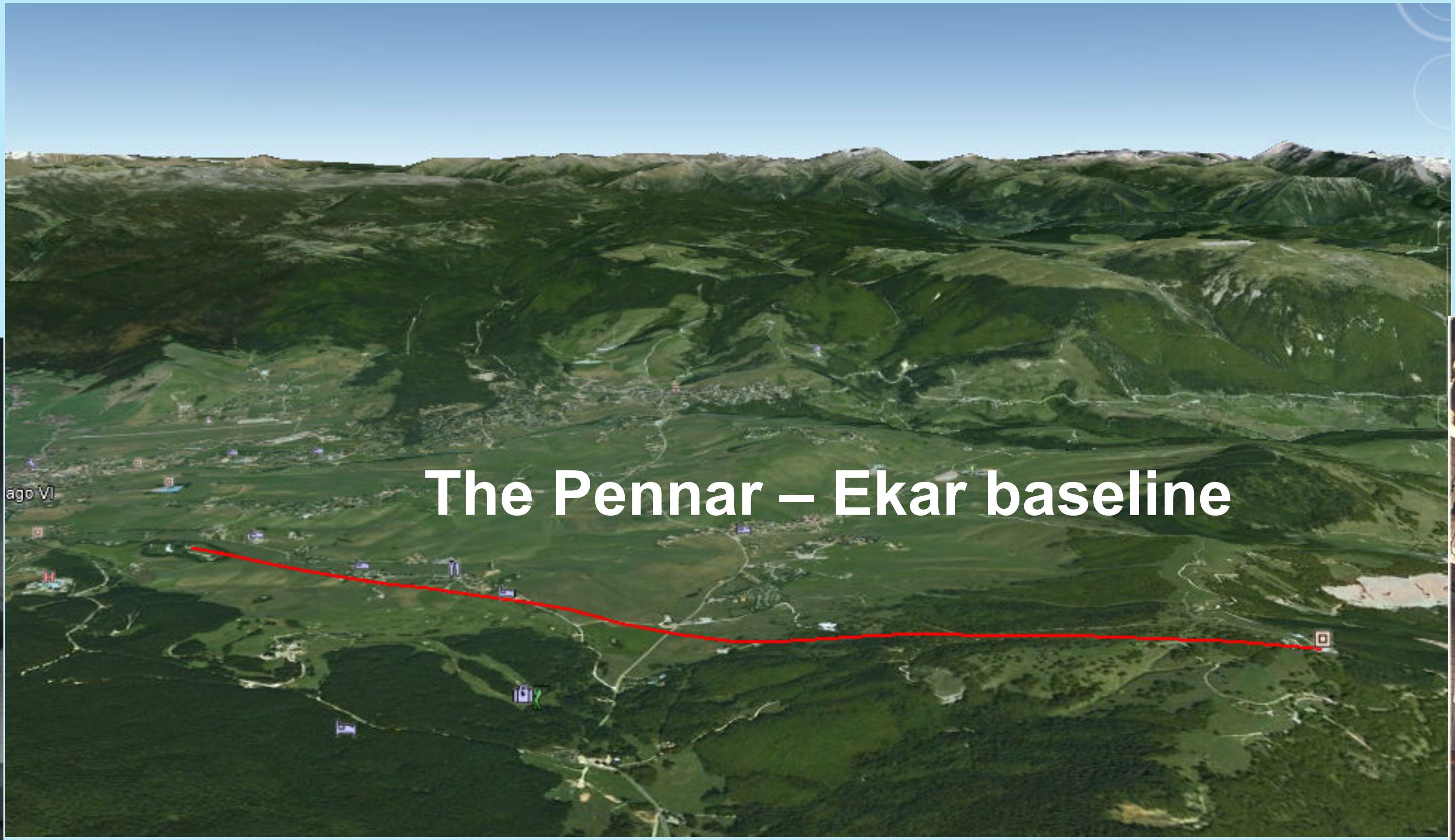
Aqueye and Iqueye are now both in Asiago

Having two identical photometers with the same accurate time frame provides another unique capability, namely the ***simultaneous observation*** of a celestial source with two distant, ***non optically*** coupled telescopes.

In other words, we realized a modern version of the ***Intensity Interferometry*** first performed by Hanbury Brown and Twiss at Narrabri more than 5o years ago.

The first successful attempts have already been made and are here reports.

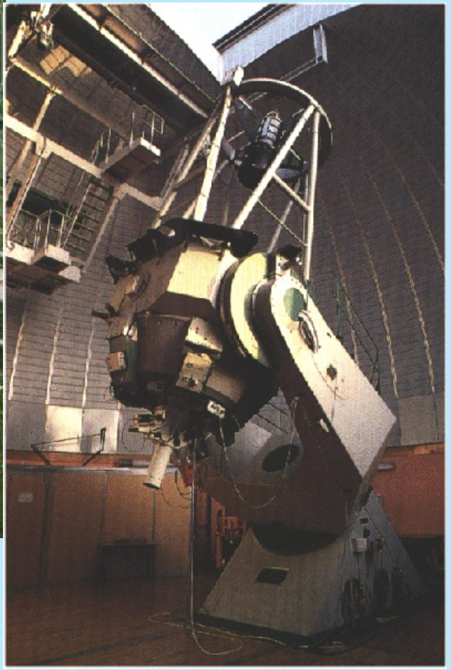
The Pennar - Ekar baseline



The elevation of the T182 is 281.8m higher than that of the T122.

T122 Galileo at Pennar station Elevation 1096.6 m

Maximum projected baseline T182-T122 (m)
3213.8 (E-W)
2133.6 (N-S)
3857.6 (Total)



T182 Copernicus at Cima Ekar Elevation 1376.2 m

The Asiago Stellar Interferometry (SII) $g^{(2)}$ measurement

$$g^{(2)}(\tau,d) = N_{T1\text{-}T2} N_b / N_{T1} N_{T2}$$ **(second order correlation function)**

τ = relative delay

d = distance between the two telescopes

N_{T1}, N_{T2} = number of photons detected at the two telescopes in interval **T = 8.64s**

$N_{T1\text{-}T2}$ number of simultaneous detections in small time bins **dt = 400 ps in T**

N_b = T/dt = 2.16×10^{10} number of bins in interval T

$g^{(2)}$ is calculated in all intervals of an acquisition and values are then averaged

Celestial source: the bright star Vega (α Lyrae)

Spectral Type A0-V, apparent mag. V = 0,

apparent diameter 3.28 ± 0.01 milliarcseconds (mas)

Measurement at zero baseline and calibration

The optical design of Aqueye+ allows us to perform measurements of the temporal correlation **at zero baseline** using the detectors in the four sub-apertures A, B, C, D

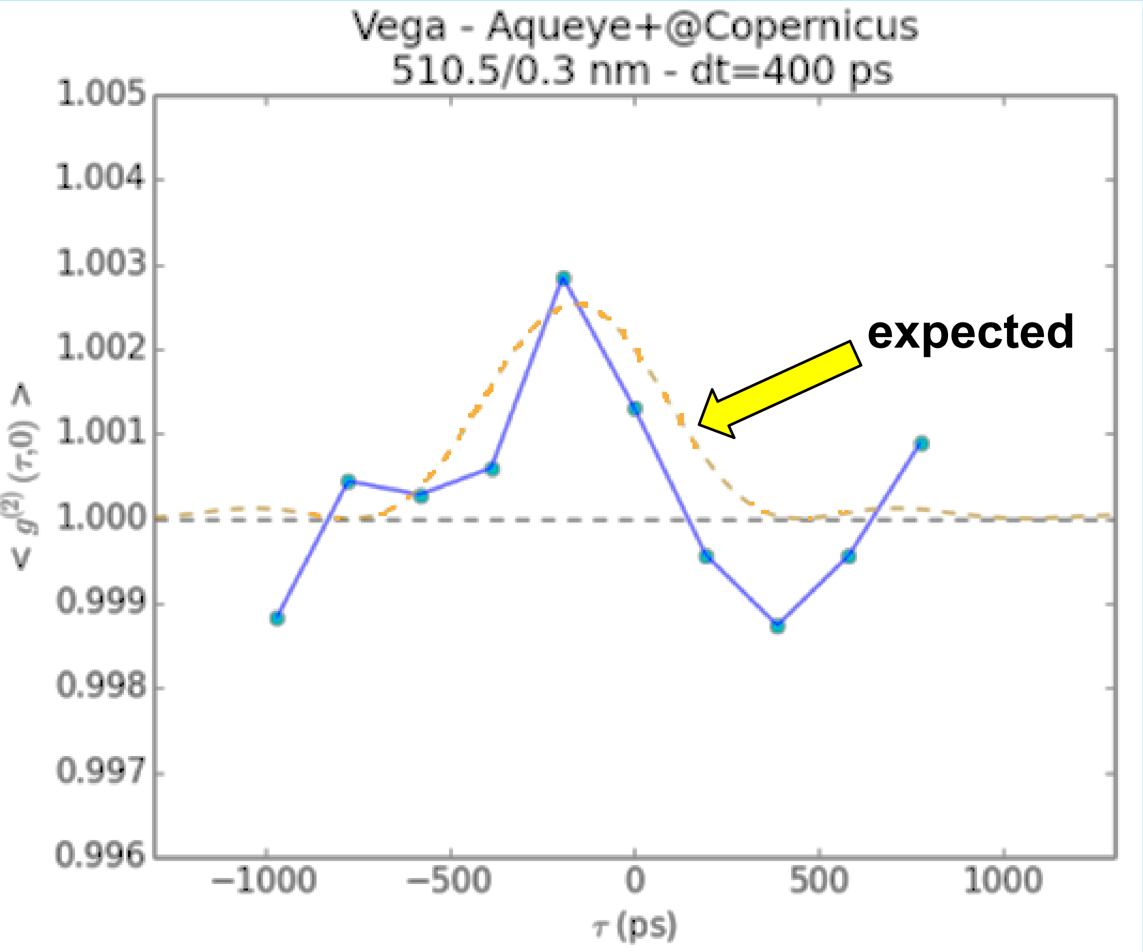
$\mathbf{g^{(2)}(\tau.0) = N_{X\text{-}Y} N_b / N_X N_Y}$ [X, Y] are combinations of the sub-apertures

In order to o remove systematics at zero baseline, $g^{(2)}$ is calibrated using **two different filter sets**:

$$\mathbf{g^{(2)} = 1 + \left[g^{(2)}(II) - g^{(2)}(H\alpha + ND1) \right]}$$

where:
(II) = Narrow band filter 510.5 nm CW, 0.3 nm FWHM
Hα filter + 10x attenuator (Hα+ND1) = 656.3 nm CW, 3 nm FWHM + ND1

Measurement of $g^{(2)}(\tau,0)$ from Vega at zero baseline with Aqueye



Calibrated temporal correlation at zero baseline $<g^{(2)}(\tau; 0)>$ in the interval of delays
τ = [-1; 0:8] ns
τ for all the Aqueye observations of Vega.
The **dashed yellow line** shows the expected profile of the temporal correlation.

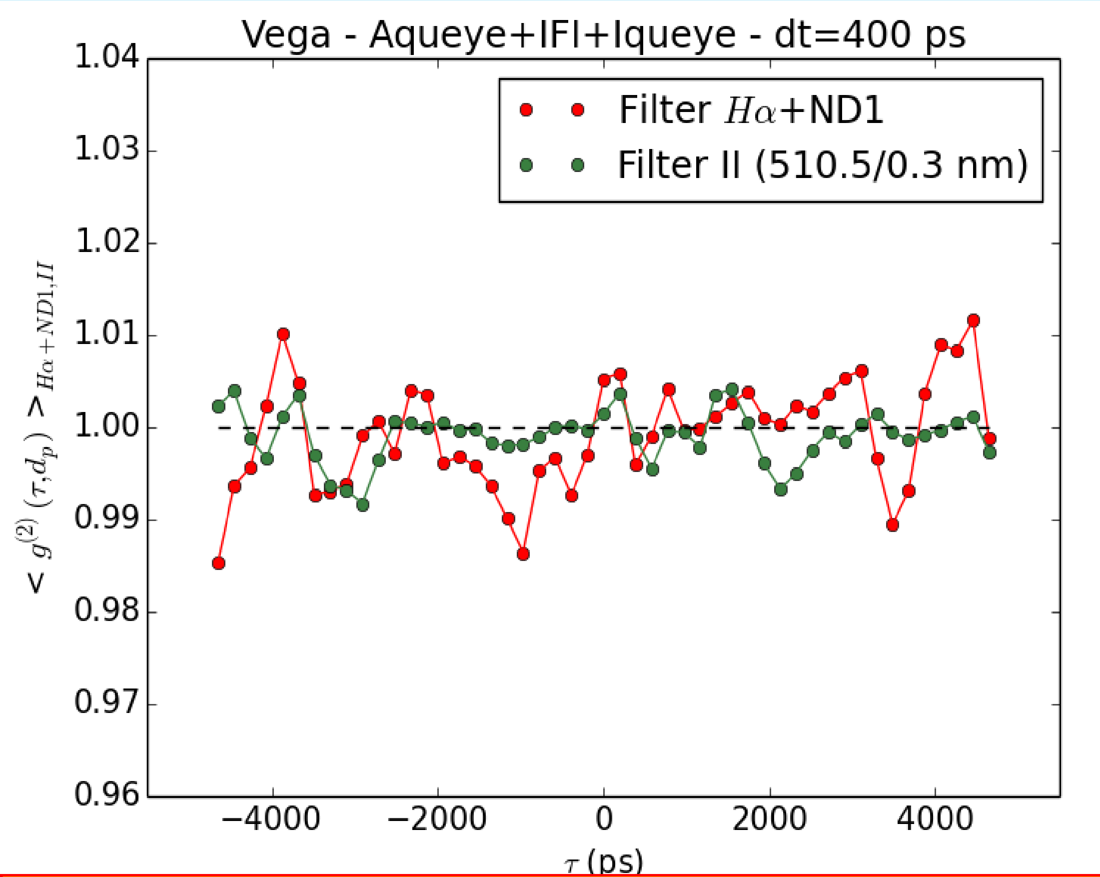
Average rate of the sub-apertures: 0.8 Mc/s

$$\mathbf{g^{(2)}(0,0) = 1.0034 +/- 0.0008}$$

Signal-to-noise ratio of measurement: S/N = 4

First successful measurement of the temporal correlation of a star at zero baseline, counting coincidences in post-processing

Measurement of $g^{(2)}(\tau, d_p)$ from Vega on a ~4 km baseline with Aqueye + Iqueye and two filter combinations



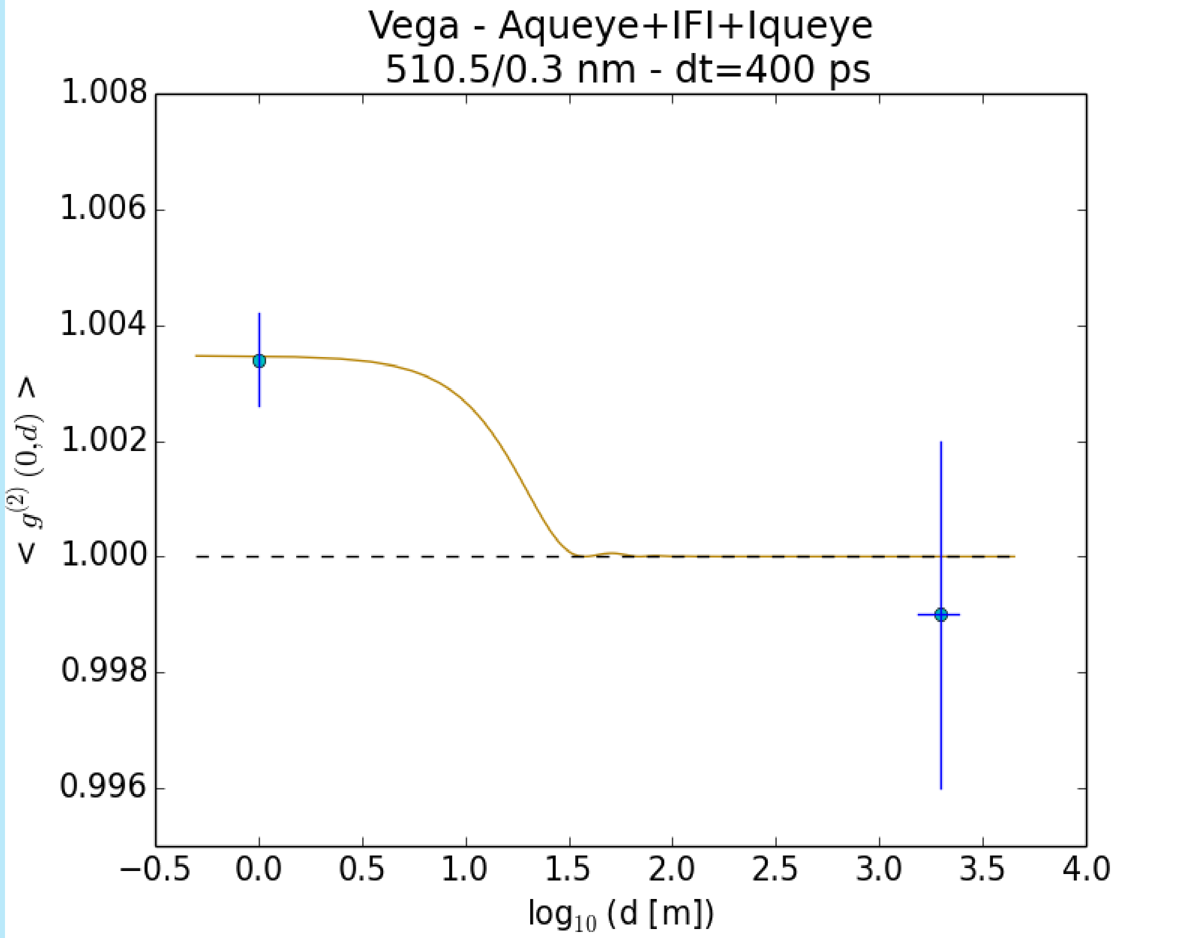
Projected telescope separation: d_p = 1.5-2.4 km
Average of count rates: 0.7 Mc/s
Time bin dt = 400 ps.
Data corrected for the light travel time delay between telescopes.

$$\mathbf{g^{(2)}(\tau, d_p) = 0.9996 \pm 0.0039}$$

No correlation, as expected for Vega on this baseline (apparent diameter 3.3 mas)

Simultaneous observations of Vega with two telescopes: first measurement of the temporal correlation of a star on a ~4 km baseline, counting coincidences in post-processing

The spatial correlation $g^{(2)}(0,d)$ of Vega



The average spatial correlation for the Aqueye + Iqueye observations of Vega at separations between 1.4 and 2.4 km is:

$$< g^{(2)} (0; d) > = 0.999 \pm 0.003$$

The yellow solid line in the figure represents the theoretical $g^{(2)}$ for a uniform brightness disc of 3.3 mas (Vega diameter). Superimposed our measurements at zero separation (left point) and at separations between 1.4 and 2.4 km (right point).

Conclusions from the Asiago experiment

The Asiago experiment provides another proof of the feasibility of Stellar Interferometry (SII), namely the possibility to measure the $g^{(2)}$ correlation function of a celestial source by entirely exploiting the quantum properties of its light.

Unlike the original Hanbury Brown and Twiss experiment, that correlated in real-time the currents from two photomultipliers, the Asiago measurements have been obtained for the first time by counting photon coincidences in post-processing by means of a single photon software correlator.

Post processing has the advantage that the data reduction chain can be repeated several times **by changing parameters** such as the time bins or the acquisition intervals, in order to check for systematics, optimize the procedure, and increase the accuracy of the results. Moreover, it will enable the computation of correlations between three or more telescopes.

Future prospects

- The Asiago experiment, although limited by the small size f the telescopes, provides a preparatory activity for future implementations of SII on larger Cherenkov telescopes arrays (CTA).

- In this context, we are working to the implementation of a SII module, using a similar photon counting approach, for the ASTRI Cherenkov telescopes to be located at the Teide facility in Tenerife.

The ASTRI Mini array

The Horn 4 m prototype of ASTRI telescopes.

Optical design: Schwarzschild – Couder

FoV: 1 degree.

Point source FWHM: 5 arcsec

It will be composed by 9 telescopes, evolution of the ASTRI-Horn prototype successfully implemented and tested on the Etna Observatory. It will deployed at the Teide Observatory (Canary Islands) in collaboration with IAC

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A list of References ***(numbering 62)*** is given in:

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THANK YOU!

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