Basics of Aqueye and of its acquisition software

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University of Padova (Italy)

VERY HIGH TIME AND SPACE RESOLUTION ASTROPHYSICS
Asiago Winter School
27 February - 7 March 2013

Part I: “Basics of Aqueye”

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Introduction

We realized in Padova two similar instruments, AquEYE and IquEYE, for astronomical applications .

They are essentially extremely fast photon counters, with the capability of time tagging the collected photons with a 50 ps time accuracy and of storing all the timing data in a mass memory.

This type of instrument is extremely versatile:

- the capability of realizing all the data analysis in post-processing allows to realize time-resolved photometry with a selection of time bin ranging from nanoseconds to minutes
- it allows to make simultaneous observations with distant telescopes, if a suitable synchronization is possible. This allows to correlate data between different telescopes, with the only limitation of the accuracy in timing.

The team

Many people have been participating to the realization of this project:

UPD: C. Barbieri, G. Naletto, G. Anzolin, I. Capraro, G. Codogno, V. Da Deppo, C. Facchinetti, C. Germanà, E. Giro, T. Occhipinti, E. Verroi, M. Zaccariotto, L. Zampieri, P. Zoccarato, …

INAF Rome: A. Di Paola

INAF Cagliari: P. Bolli, C. Pernechele

INAF Catania: S. Billotta, G. Bonanno

Collaborations: D. Dravins (Lund), A. Cadez (Ljubljana)

Outline

- Short history: QuantEYE
- Description of Aqueye: optics, detectors, electronics, performance
- Some example of the obtained results

QuantEYE

OWL Instrument Concept Study

QUANTUM OPTICS INSTRUMENTATION FOR ASTRONOMY

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LUND UNIVERSITY

OWL-CSR-ESO-00000-0162

In Sept. 2005, we completed a study (QuantEYE, the ESO Quantum Eye) in the framework of the studies for the 100 m diameter Overwhelmingly Large (OWL) telescope.

The main goal of the study was to demonstrate the possibility to reach the picosecond time resolution (Heisenberg limit) needed to bring quantum optics concepts into the astronomical domain, with two main scientific aims in mind:

- to measure the entropy of the light beam through the statistics of the photon arrival time

- to demonstrate the feasibility of a modern version of the Hanbury Brown Twiss Intensity Interferometry

QuantEYE: the possibility of making very HTRA

This study highlighted the possibility of a side application of QuantEYE, that is a very high time resolution astronomy. In fact, the time resolution performance of QuantEYE allowed to overcome the microsecond barrier, going down to nano- and sub-nanosecond regime.

With such an ultrafast photometer several astrophysical phenomena can be deeply investigated, bringing potentially new information on some not yet well understood celestial objects:

- Variability near black holes
- Surface convection on white dwarfs
- Non-radial oscillations in neutron stars
- Surface structures on neutron-stars
- Photon bubbles in accretion flows
- Free-electron lasers around magnetars
- Astrophysical laser-line emission (requiring spectral resolutions reaching $R = 10^8$)
- Quantum statistics of photon arrival times

A major key limitation: the detector

The most critical point, and driver for the possible optical designs of QuantEYE, was the availability of very fast and accurate photon counting detectors.

- Imaging PC detectors (ICCD, ICMOS, MCP) either do not allow fast time tagging of the detected events, or have a rather low maximum total count rate

- Non-imaging PC detectors (PMT, SPADs) either have a relatively low QE, or have a small sensitive area

Having in mind the need of reaching sub-ns time accuracy, SPADs are preferable: a 50 ps time resolution with count rates as high as 10 MHz can be obtained, with standard voltages and QE.
However, even if the time resolution could be acceptable for this application, the total count rate was still two orders of magnitude smaller than what was necessary, with the strong limitation of a very small sensitive area.

Splitting the problems …

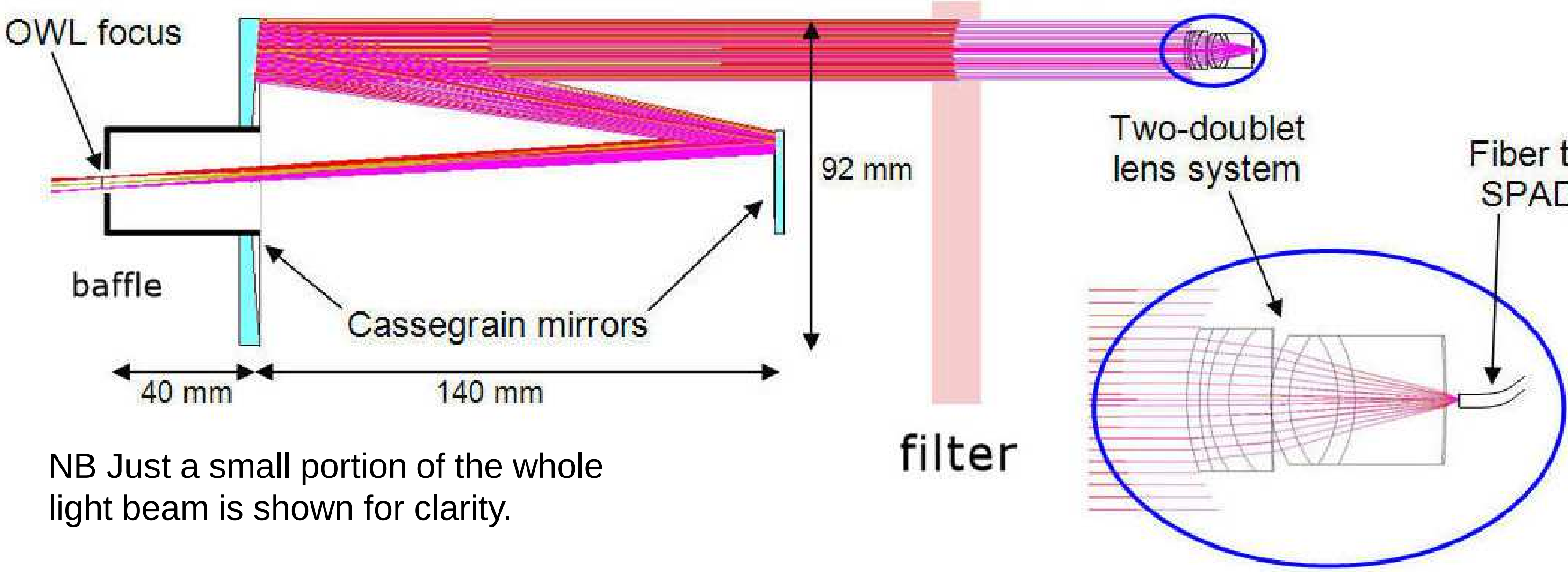
To suitably design the system and to overcome both the SPAD limitations and the difficulties of a reasonable optical design (coupling the 100 m pupil / 600 m focal length of OWL with a single 50 μm detector !), we decided to *split the problems*.

In practice, we designed QuantEYE subdividing the system pupil into $N \times N$ sub-pupils, each of them focused on a single SPAD (so giving a total of N^2 *distributed* SPAD's).

In such a way, a “sparse” SPAD array (SSPADA) coping with the required very high count rate could be obtained.

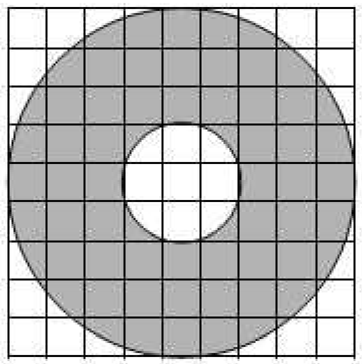
The SSPADA is sampling the telescope pupil, so a system of N^2 parallel smaller telescopes is realized, each one acting as a fast photometer.

QuantEYE optical design

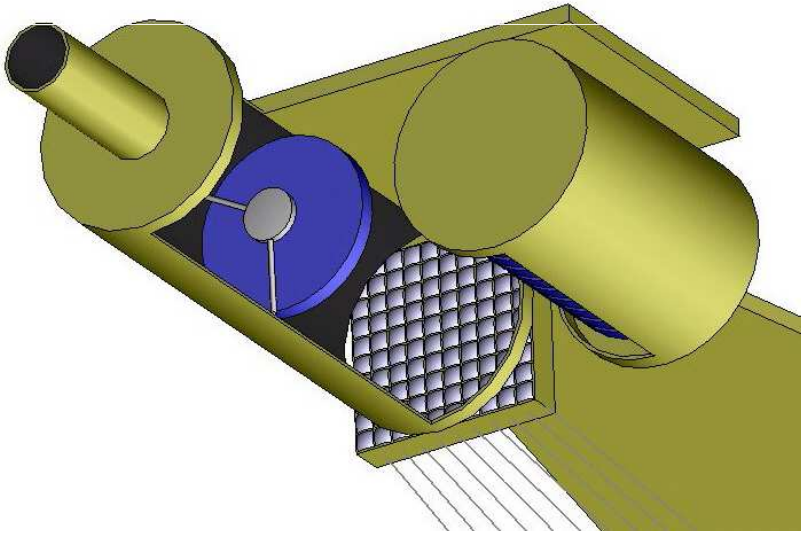


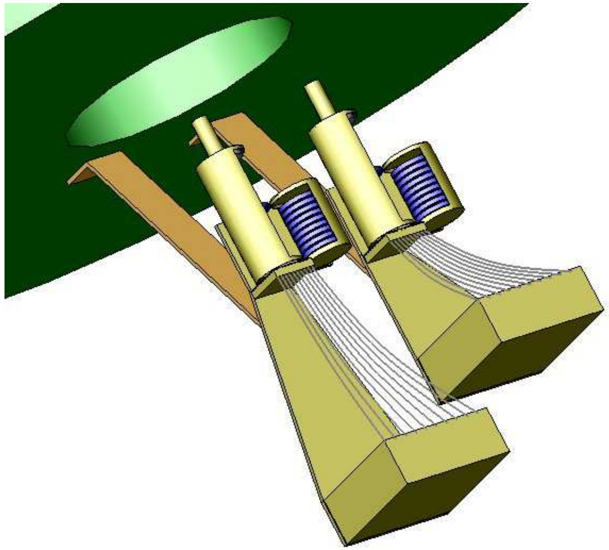
NB Just a small portion of the whole
light beam is shown for clarity.

Schematic view of the
telescope pupil subdivision



QuantEYE @ OWL

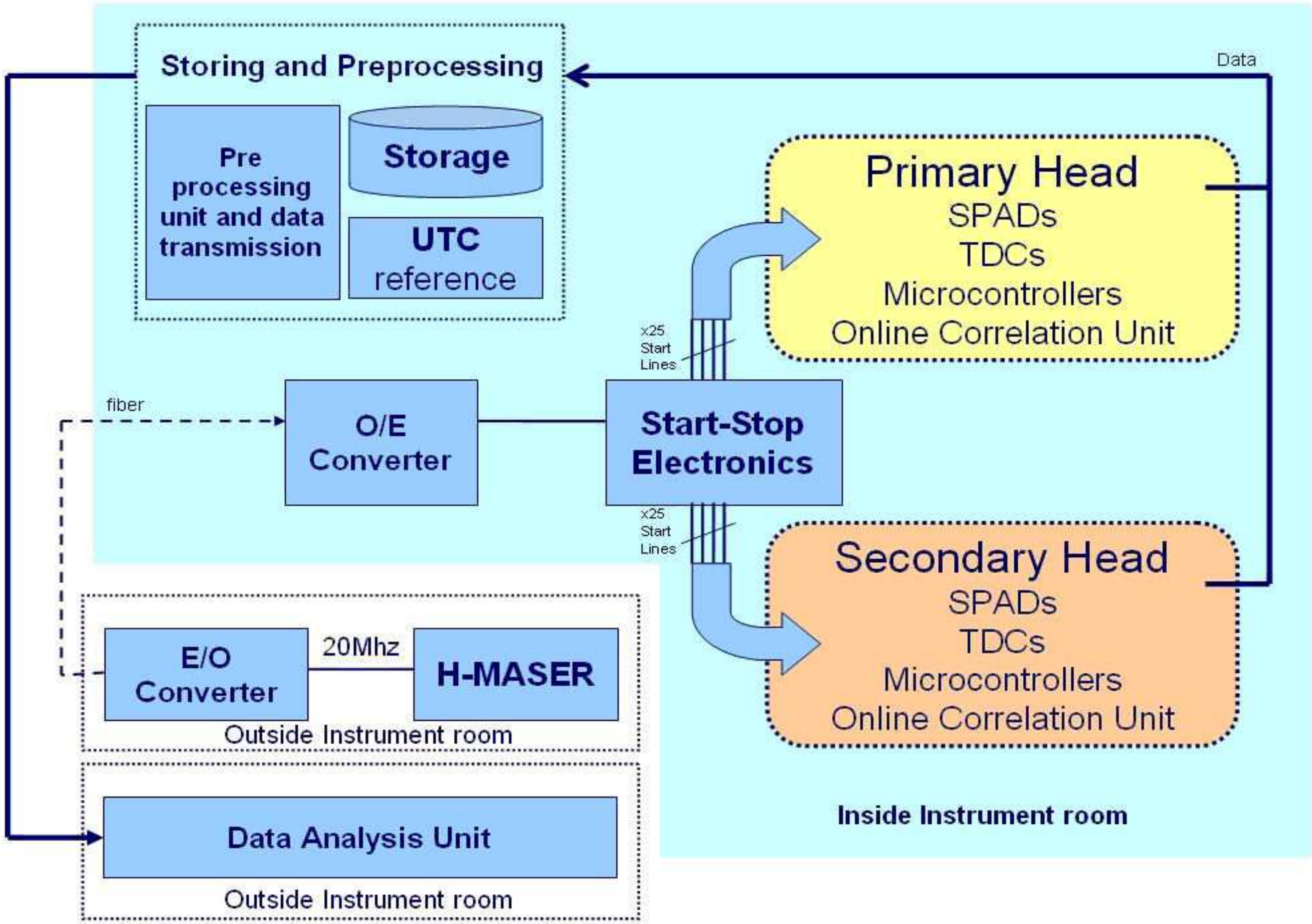




Advantages of this optical design

- The global count rate is statistically increased by a factor N^2 with respect to the maximum count rate of a single SPAD. In the assumption of having $N = 10$ (100 SPAD's), the global count rate becomes 1 GHz (one photon every 100 ns on each SPAD)
- Simpler optical design
- Detector redundancy
- By suitable cross-correlations of the detected signal, a digital Hanbury Brown & Twiss intensity interferometer is realized among a large number of different sub-apertures across the full OWL pupil

Overall QuantEYE block diagram

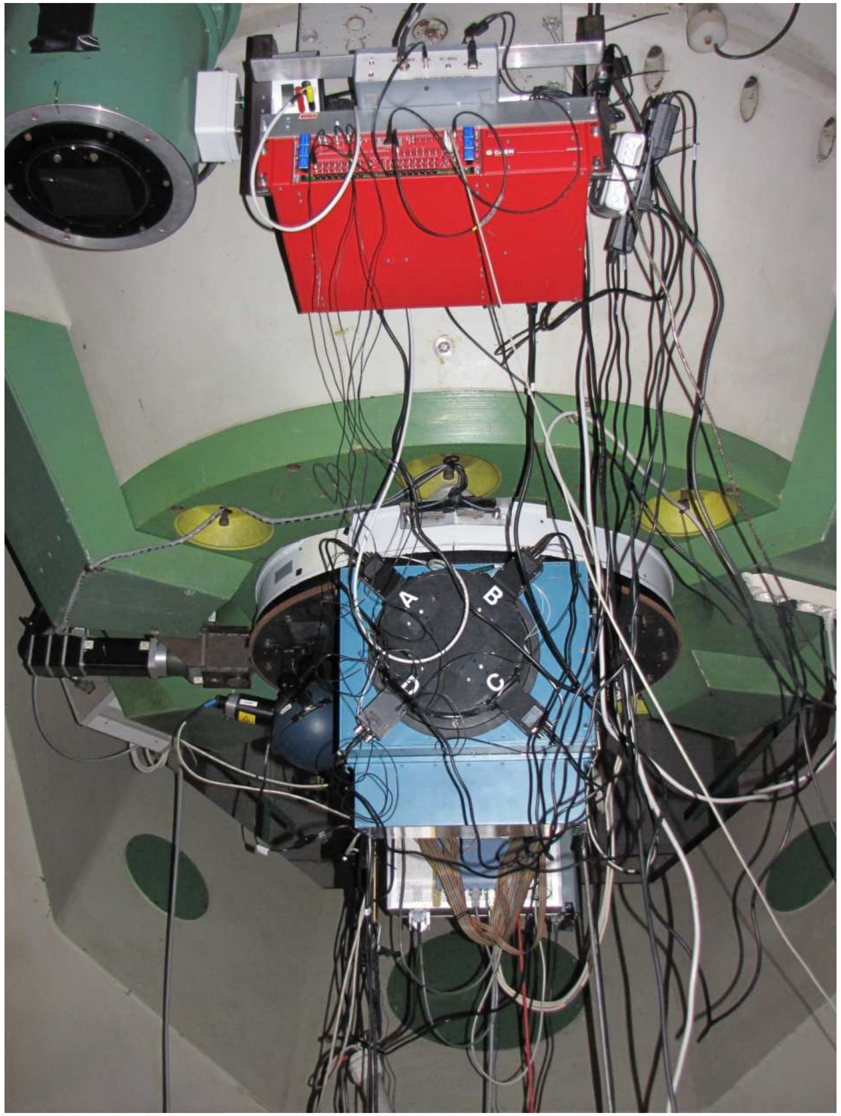


The overall system: two heads, controls, storage, time unit.

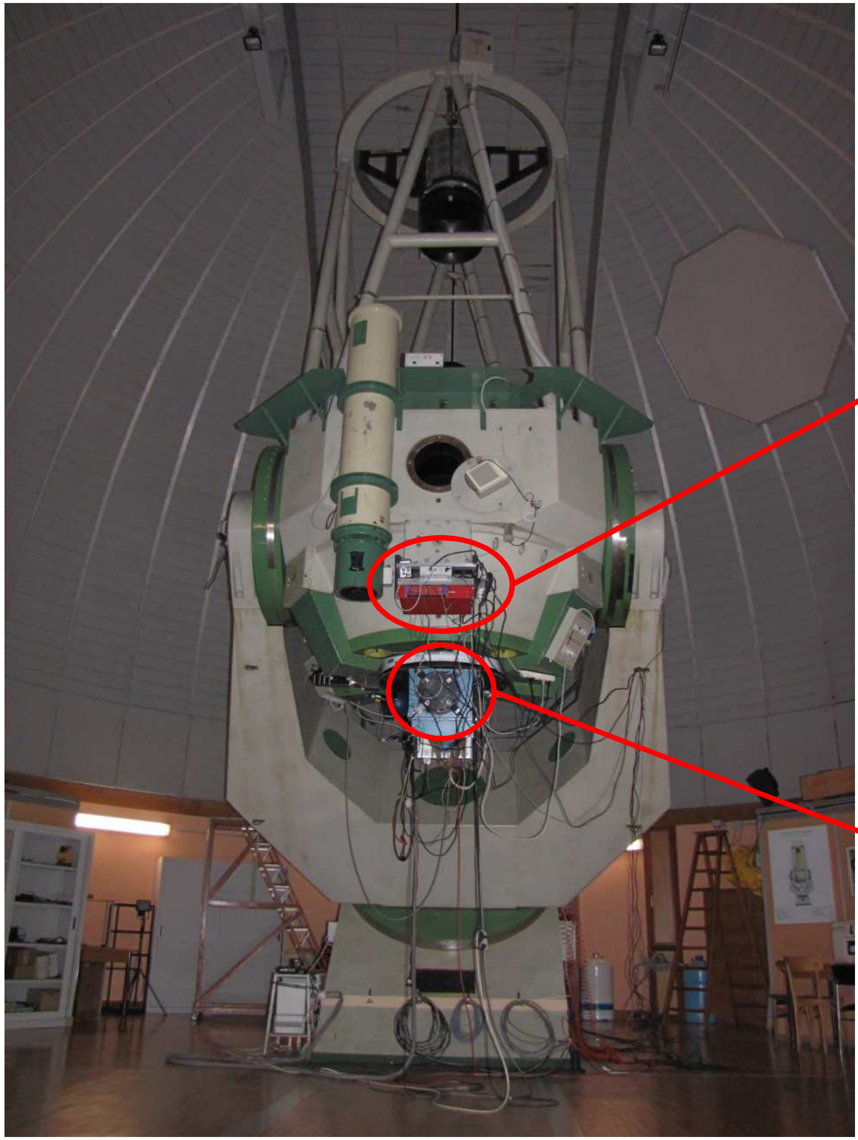
Aqueye

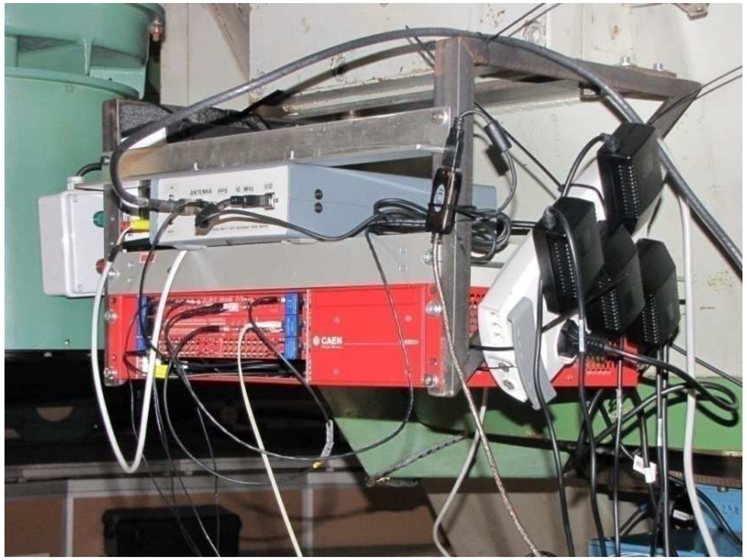
While expecting the realization of the future E-ELT (which is now foreseen to have a 39 m diameter…), we decided to apply the described concept to realize a much smaller version of the instrument, compatibly also with the few available funds.

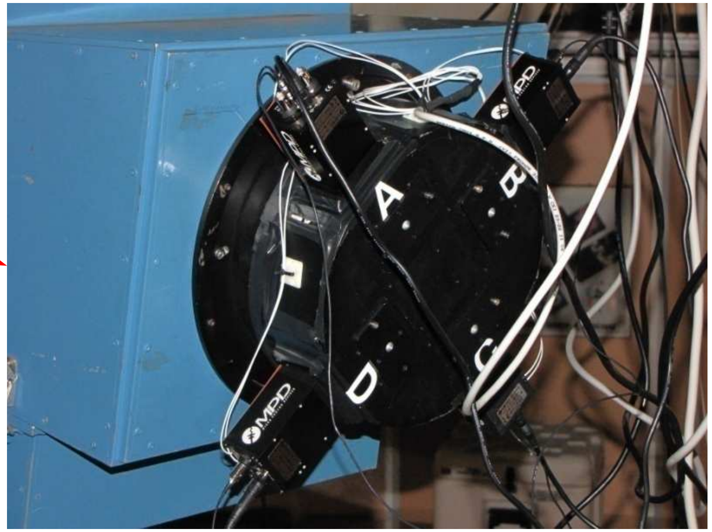
We named this instrument Aqueye, the “Asiago quantum eye”. It has been applied to the AFOSC camera of the Asiago-Cima Ekar (Italy) 182 cm Telescope.



Aqueye @ the Cima Ekar Copernicus Telescope



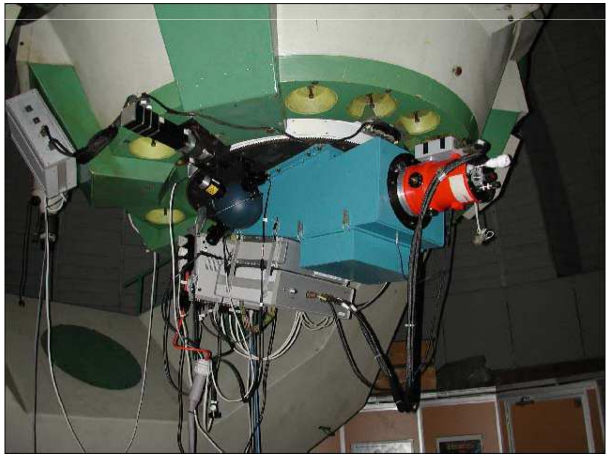


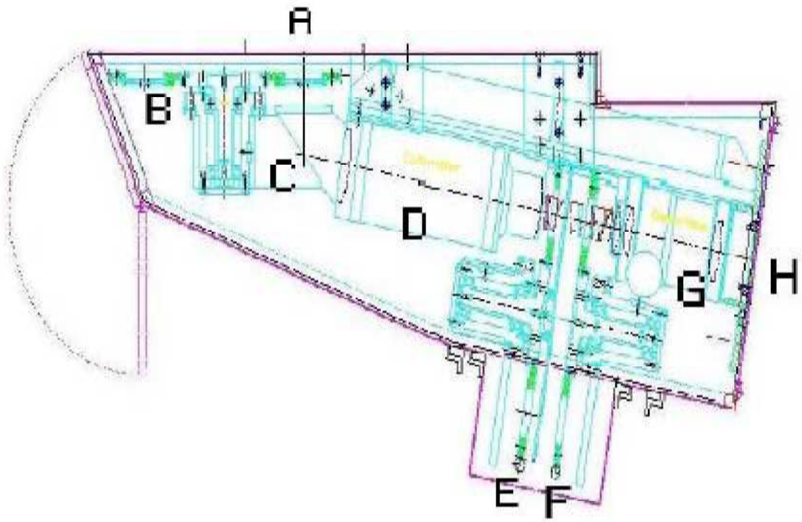


AFOSC as interface to the telescope

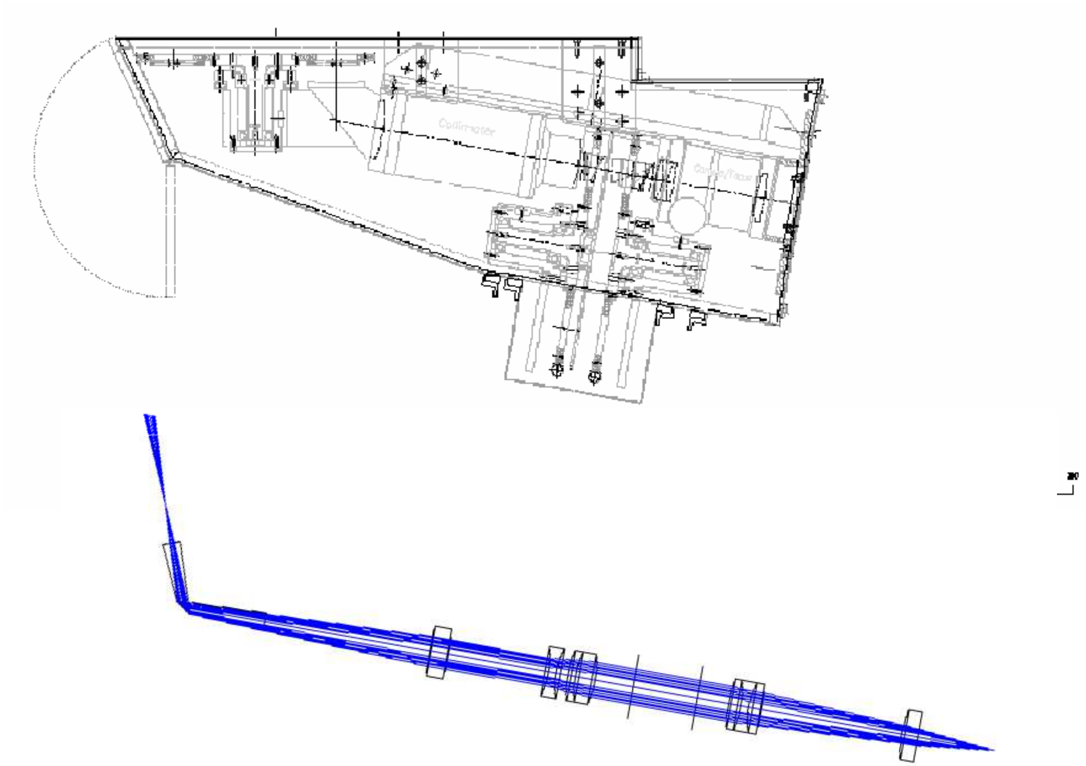
To mount Aqueye to the telescope, given the limited available resources, it has been preferred to use AFOSC (Asiago Faint Object Spectrograph and Camera) as interface. In practice, Aqueye replaces the AFOSC CCD.

AFOSC acts as a focal reducer ($\times$ 0.58) and allows the insertion of different filters/polarizers along the common optical path; it is also possible to block the light path with a shutter and to adjust the focus depth.





AFOSC: optical path & optical parameters



Optical path inside AFOSC.

Collimator Focal Length	252.1 mm
Collimator Linear Field	52.9 X 52.9 mm^2
Beam Diameter	27.8 mm
Camera Focal Length	146.3 mm
Camera Linear Field	24.58X 24.58 mm^2
Reduction Ratio	0.58
AFOSC Scale	21.70 ''/mm
Wavelength Coverage	330 - 1100 nm
Projected Pixel Size	0.''473
Field of view	8.14' X 8.14'
Limiting Spectral Resolution	5316

AFOSC filters and focus shift

Filter	λ_c nm	FWHM nm	Peak Transm.	Remarks
U	363.95	34.54	0.53	Bessel
B	420.05	72.82	0.71	Bessel
V	547.44	89.90	0.94	Bessel
R	647.59	156.98	0.86	Bessel
I	870.97	236.26	0.97	Bessel
i	785	180	0.90	Gunn
OS1				Order Separator for Gr #13
ND1	–	–	0.1	neutral filter
ND2	–	–	0.01	neutral filter
ND3	–	–	0.001	neutral filter
ND4	–	–	0.0001	neutral filter
ND5	–	–	0.00001	neutral filter

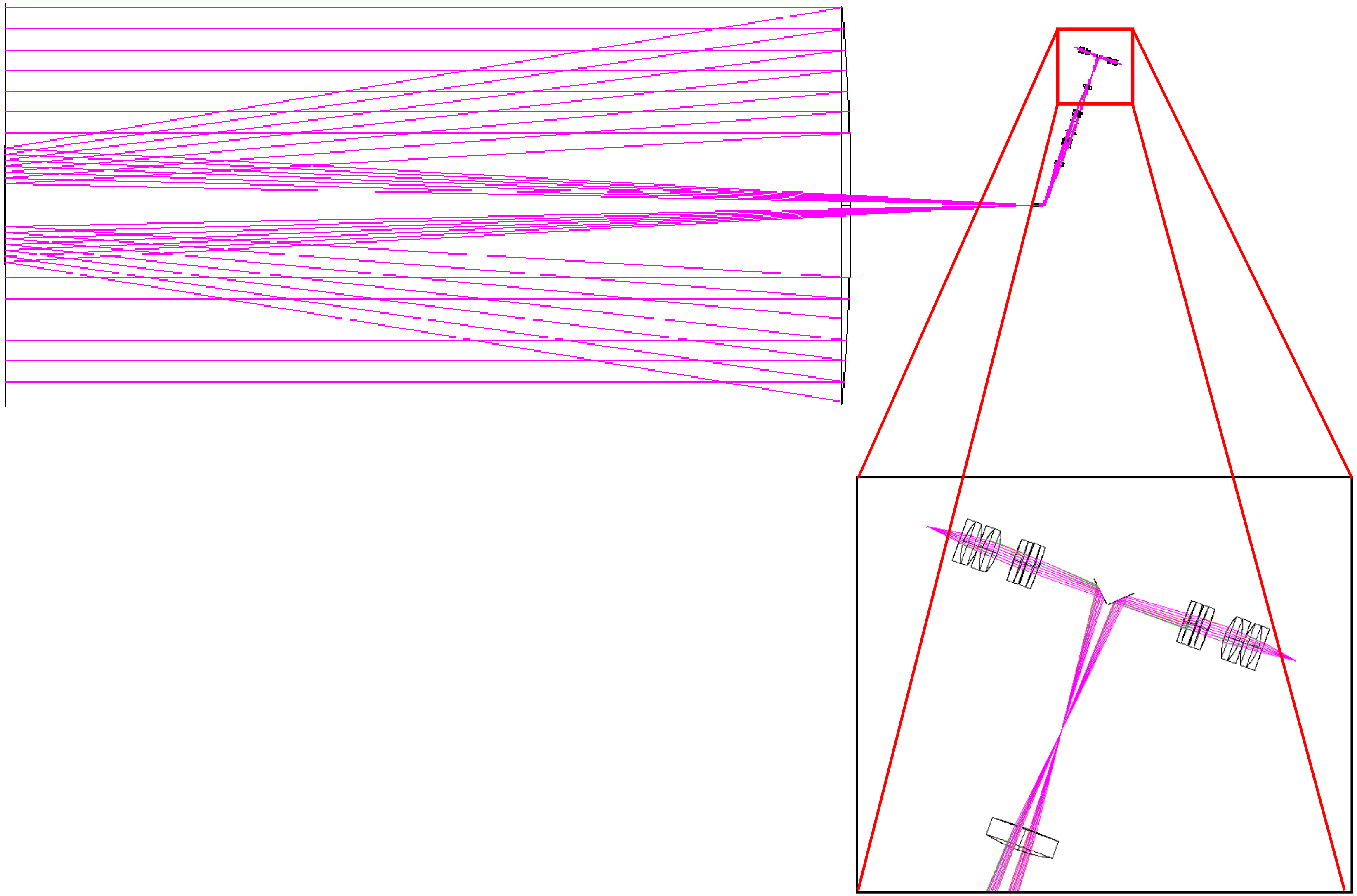
Table 2.6: AFOSC filters.

Parameter	Shift X pix	Shift Y pix	Shift Focus counts
U	5.4	0.8	–8700
B	–1.5	9.3	–5800
V	0.9	–2.9	–2500
R	–8.1	2.4	0
i	–2.1	0.5	8400
OS1	0.3	–0.6	
ND3	1.5	0.2	

Shift in position and focus caused by the filters. The focus shift is expressed in encoder counts.

(1 pixel = 0.473”)

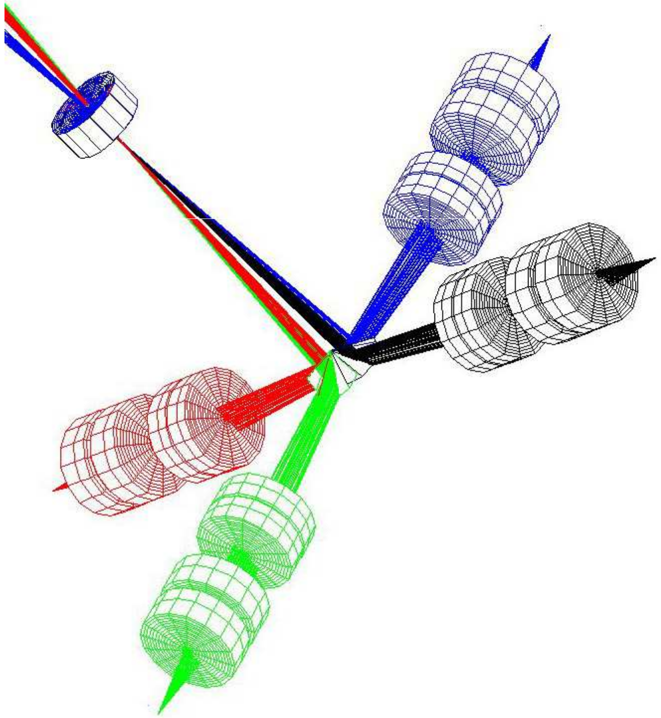
Telescope & Aqueye optical path

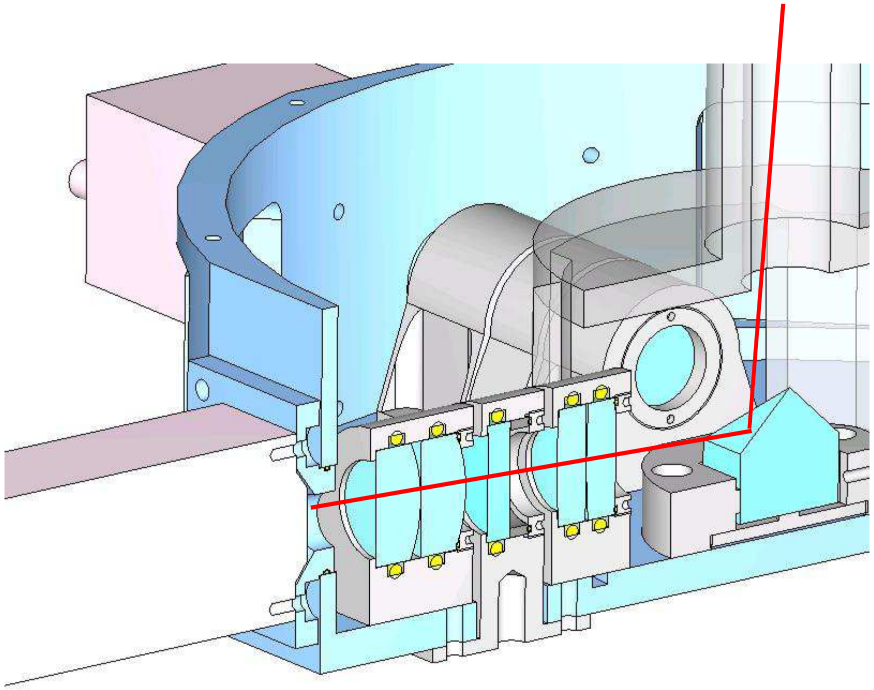


Aqueye opto-mechanical design

To realize this prototype, we used the same approach of splitting the entrance pupil adopted for IquEYE: the telescope pupil is divided in four portions, each of them focused on a single SPAD.

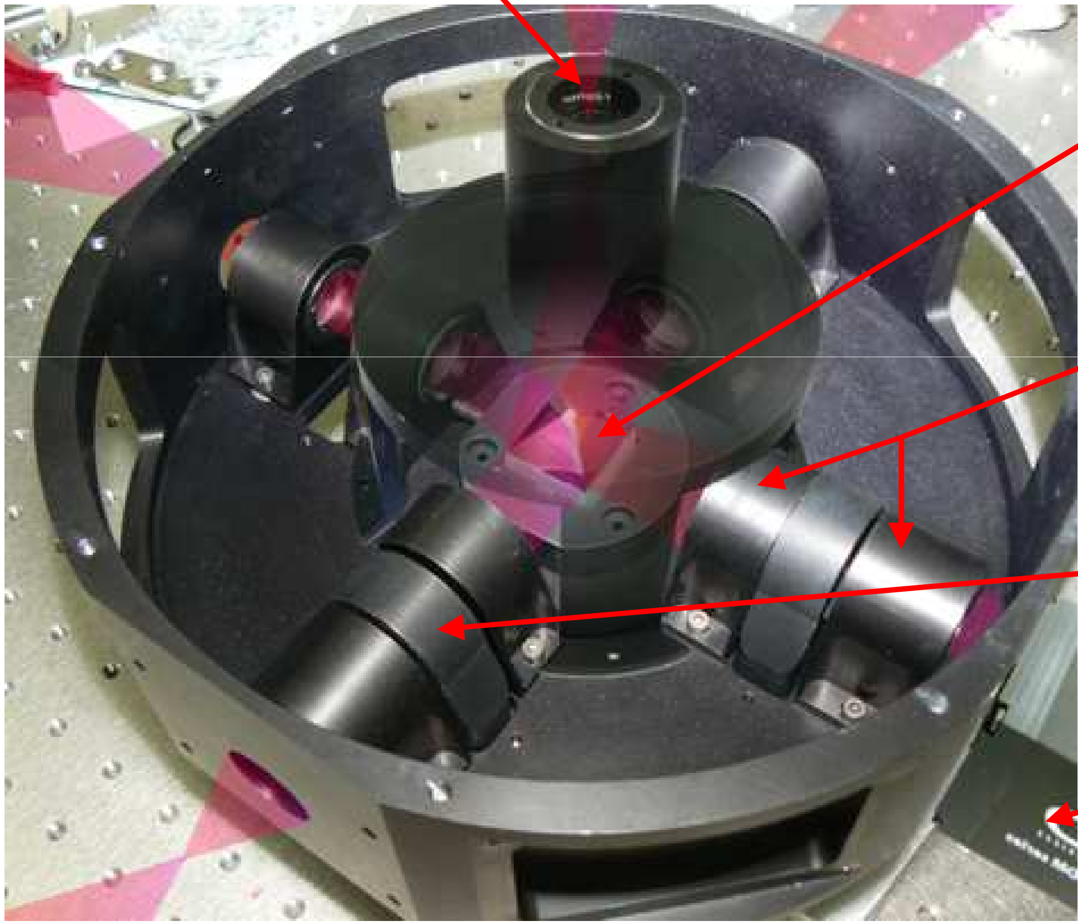
For Aqueye, a simple optical solution in which the four subpupils are defined by a pyramidal mirror has been used.

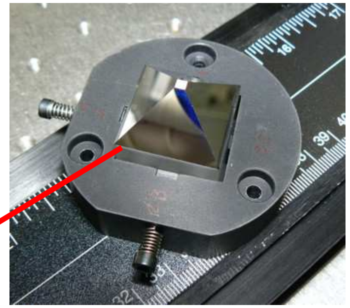




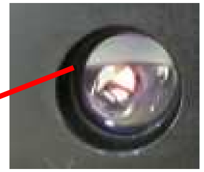
AquEYE subsystems

AFOSC focus

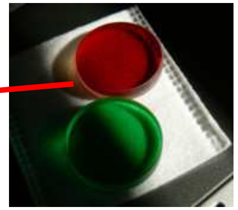




Pyramid



Focusing lenses



Filters (to be inserted by hand)

SPAD

Aqueye spot diagrams

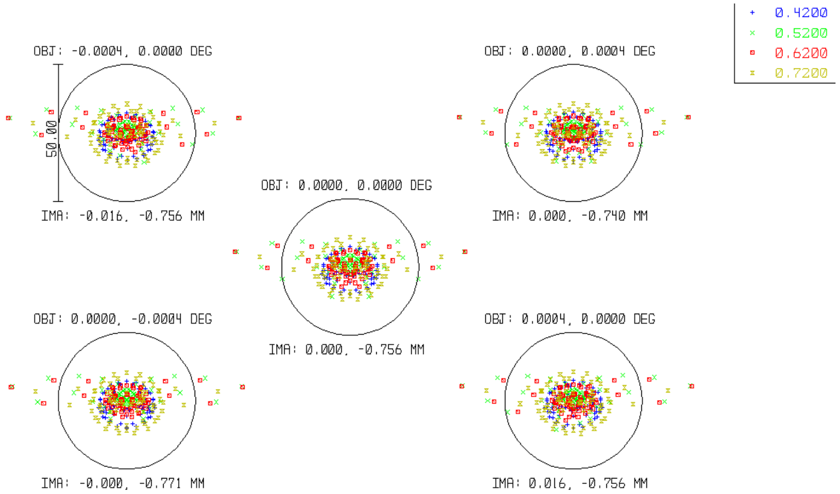
The Asiago telescope focal length is 16.1 m, and a 3 arcsec extended source (the average size of a point-like star, due to the limited seeing) gives a spot size at the telescope focus of about 230 μm.

AFOSC introduces an almost 1/2 demagnification factor, bringing the size of the spot at the AFOSC output to about 130 μm.

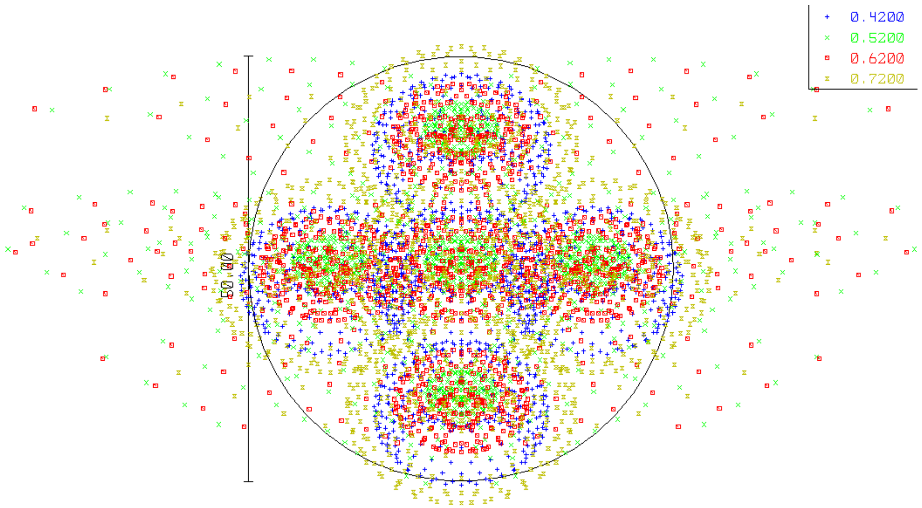
The lens train after the pyramid further demagnifies the spot of about a factor 1/4 to have a final spot size of the order of 40 μm (the original SPAD sensor had a sensitive circular area of 50 μm diameter: the new ones have a sensitive circular area of 100 μm diameter).

Source radius: 1.5 arcsec

$\Delta\lambda$ = 420-720 nm

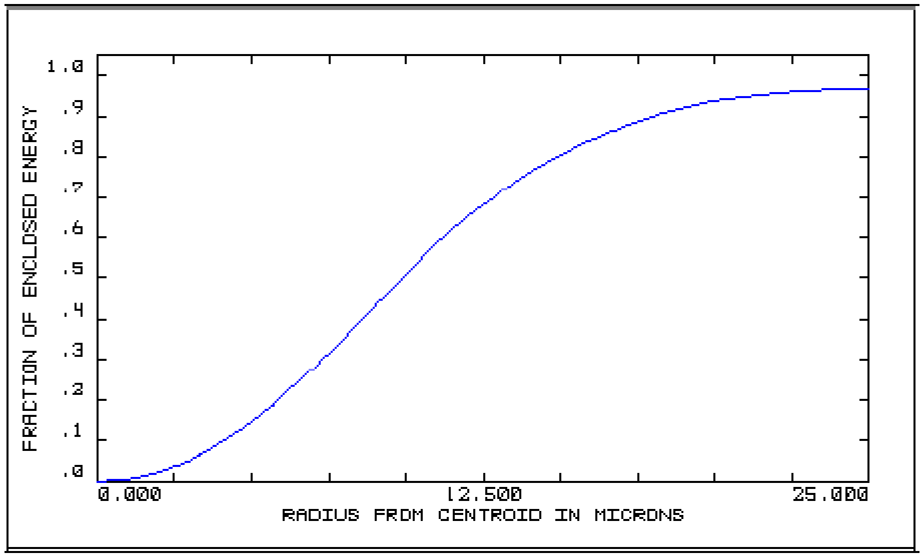


Aqueye spot performance



Source radius: 1.5 arcsec
$\Delta\lambda$ = 420-720 nm

Extended source encircled energy plot: percentage of energy falling within a circle of given radius for a uniformly illuminated 3 arcsec extended circular source.



Single Photon Avalanche Diodes (SPAD)

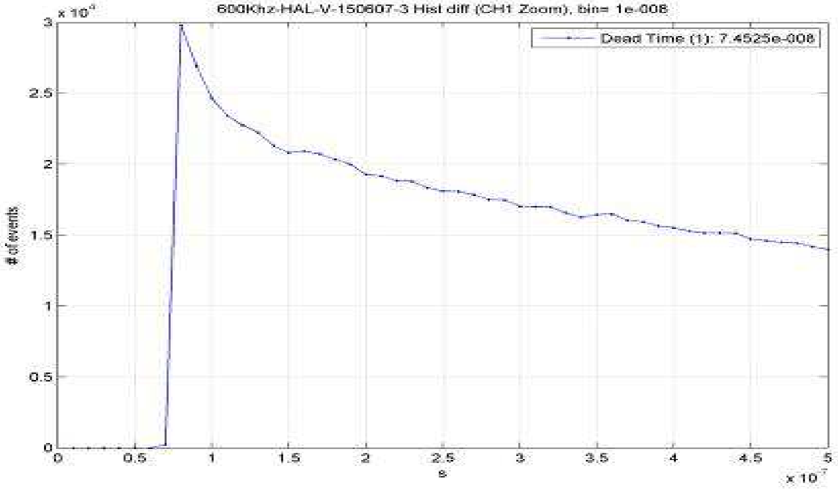
The selected detectors are SPADs produced by MPD (Italy).

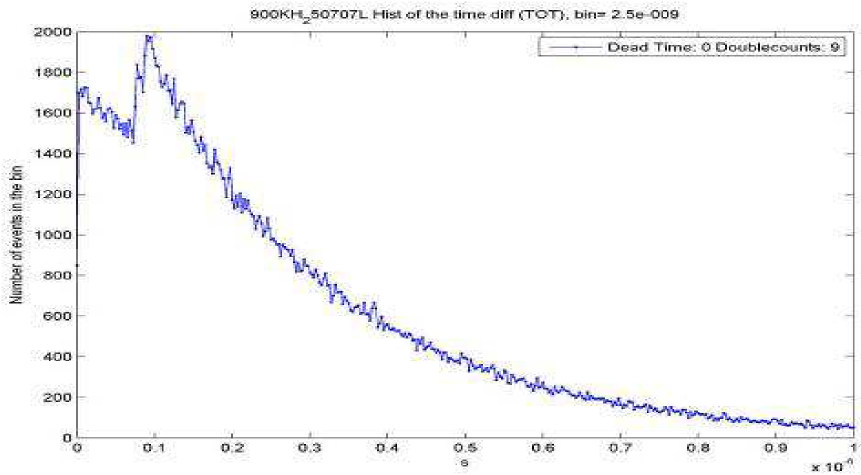
Their main characteristics are:

- 100 μm diameter active area
- can tolerate full day light
- thermoelectrically regulated
- dark count of the order of 50 Hz
- the integrated timing circuit gives a time stamping accuracy better than 50 ps
- dead time of ≈70 ns
- typical after-pulsing probability of 0.5%
- maximum count rate (linearity range): ≈ 2 MHz @ NIM output; ≈10 MHz @ TTL output
- each unit comes integrated in a box containing an active Peltier cooling stage and a time forming circuitry
- a flat BK7 window seals the active area from the ambient.

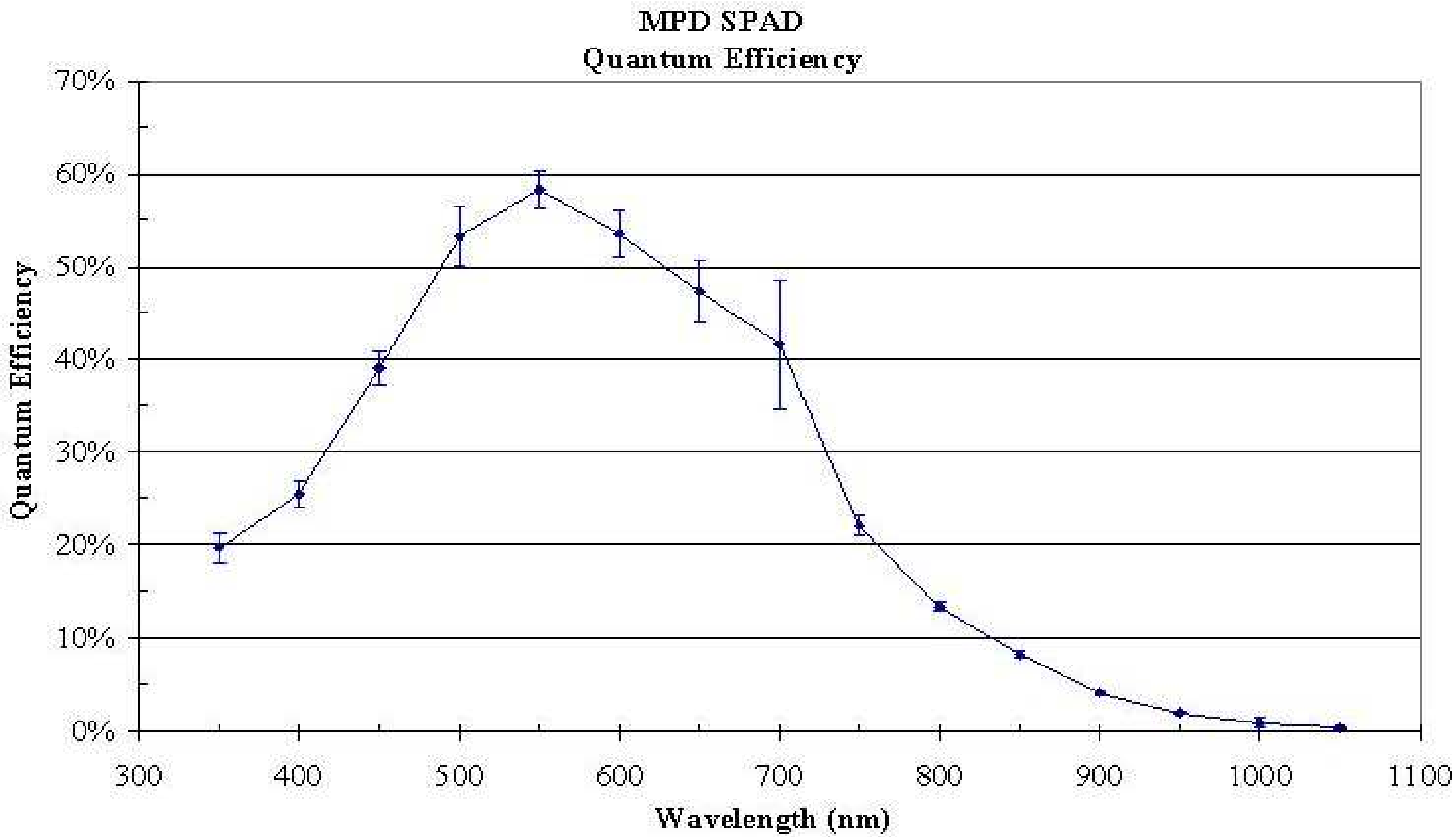
Advantage of using multiple SPADs

Differences between the measured photon times of arrival ($t_{i+1} - t_i$) when using one or four SPADs (some MHz total rate)

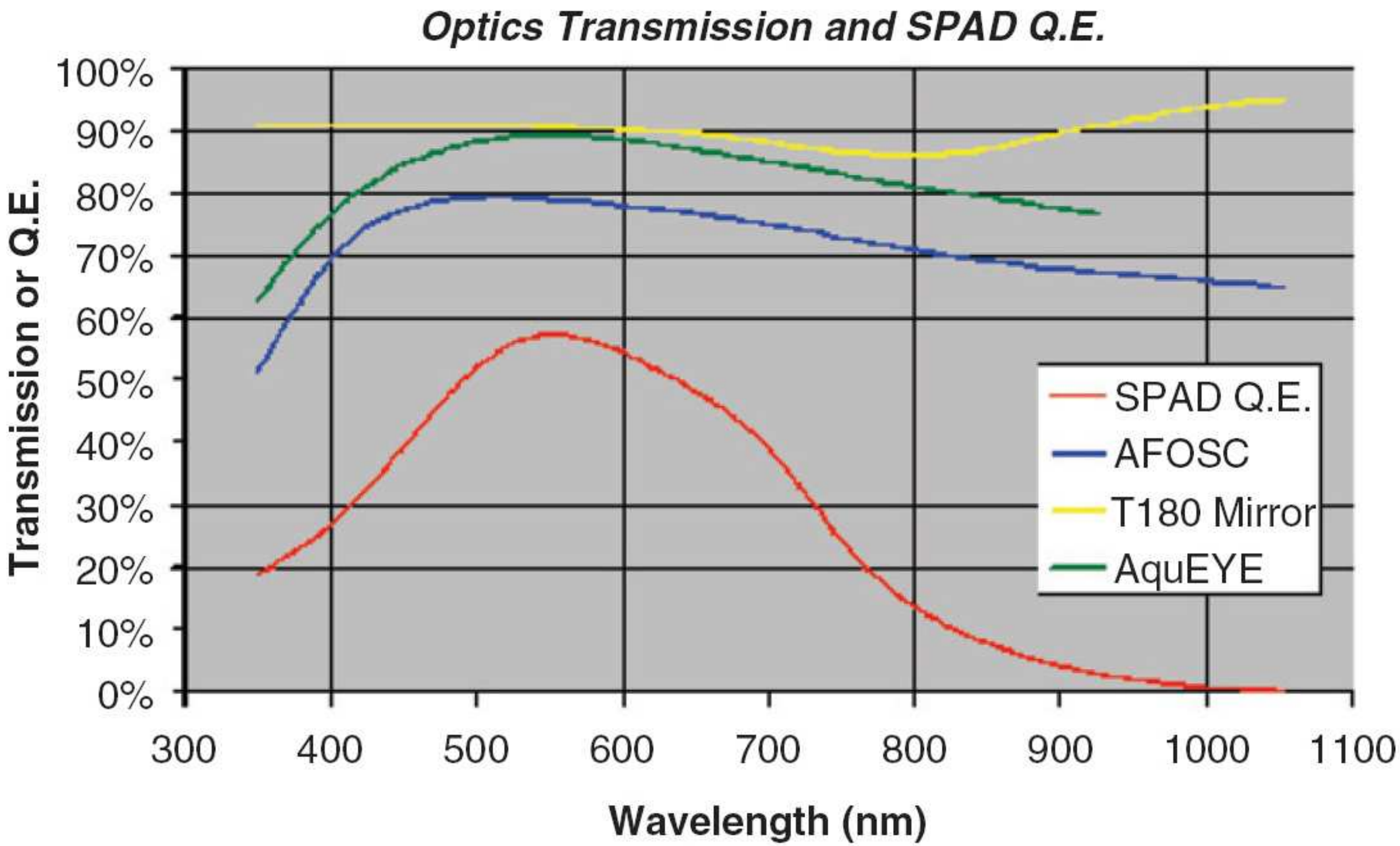




SPAD measured quantum efficiency

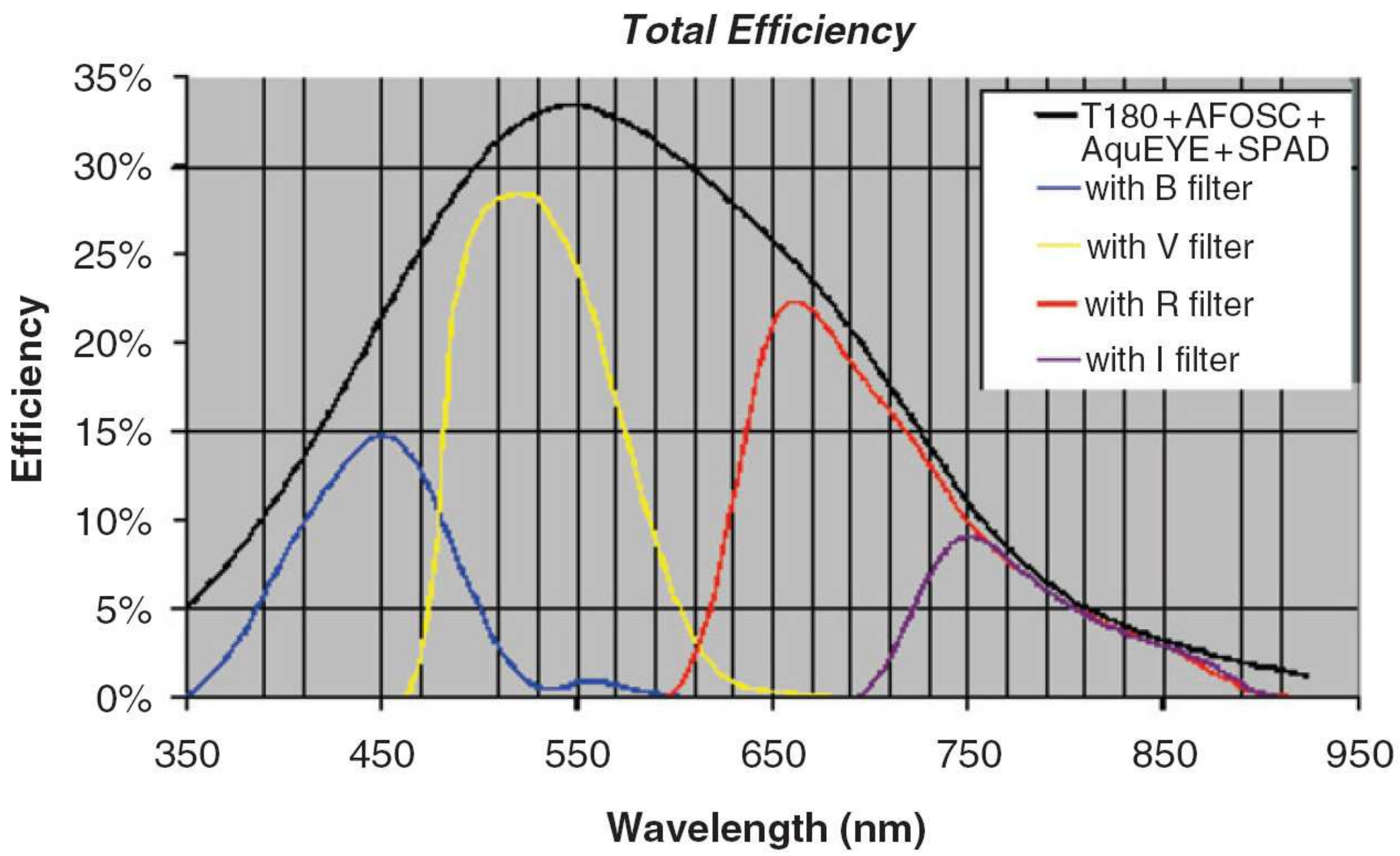


Throughput



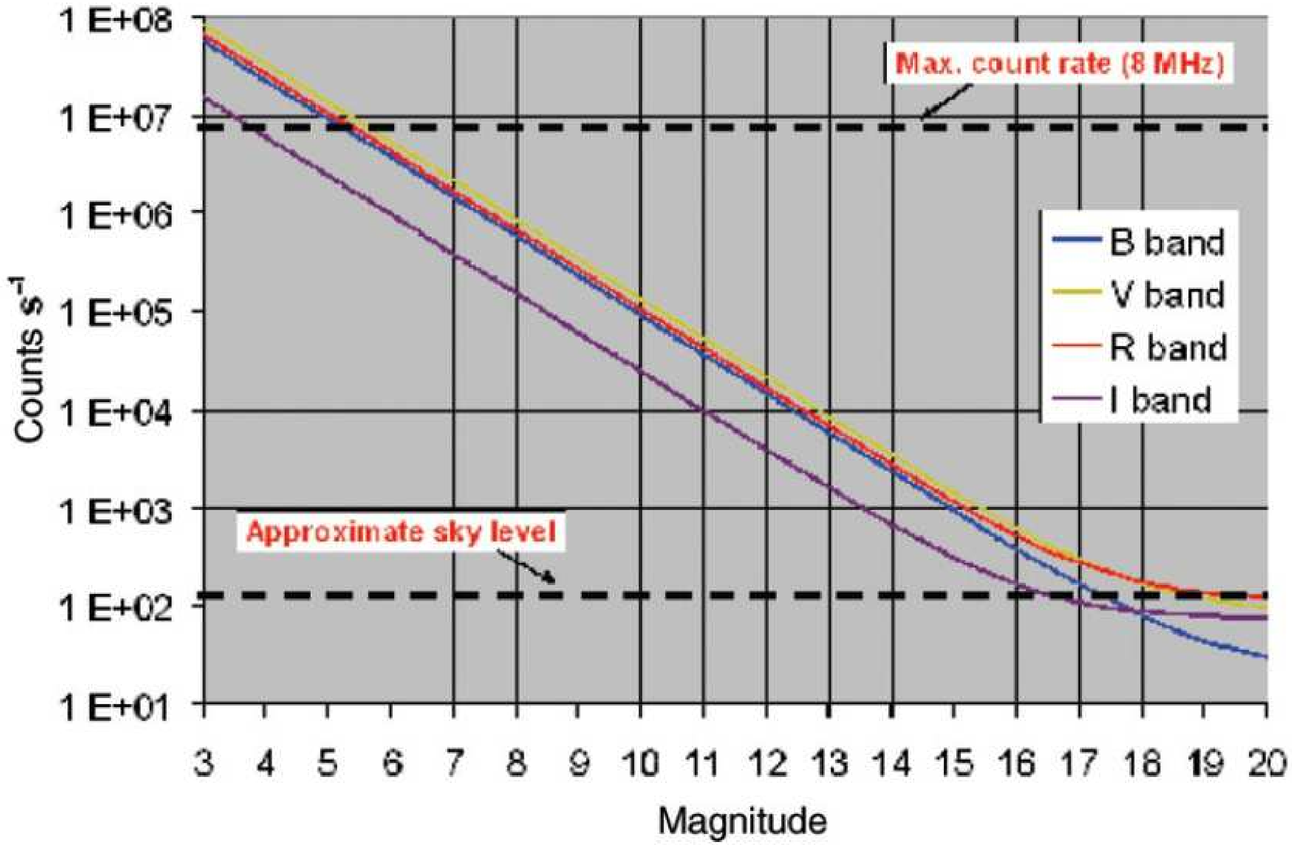
Efficiency of the single elements of AquEYE (telescope, AFOSC, pyramid, objectives, SPADs).

Total Aqueye efficiency



The overall Aqueye efficiency (black curve) convolved with the transmission of the different filters produces the global efficiency of the system. In this case, the global system efficiency when using the broadband BVRI filters is shown.

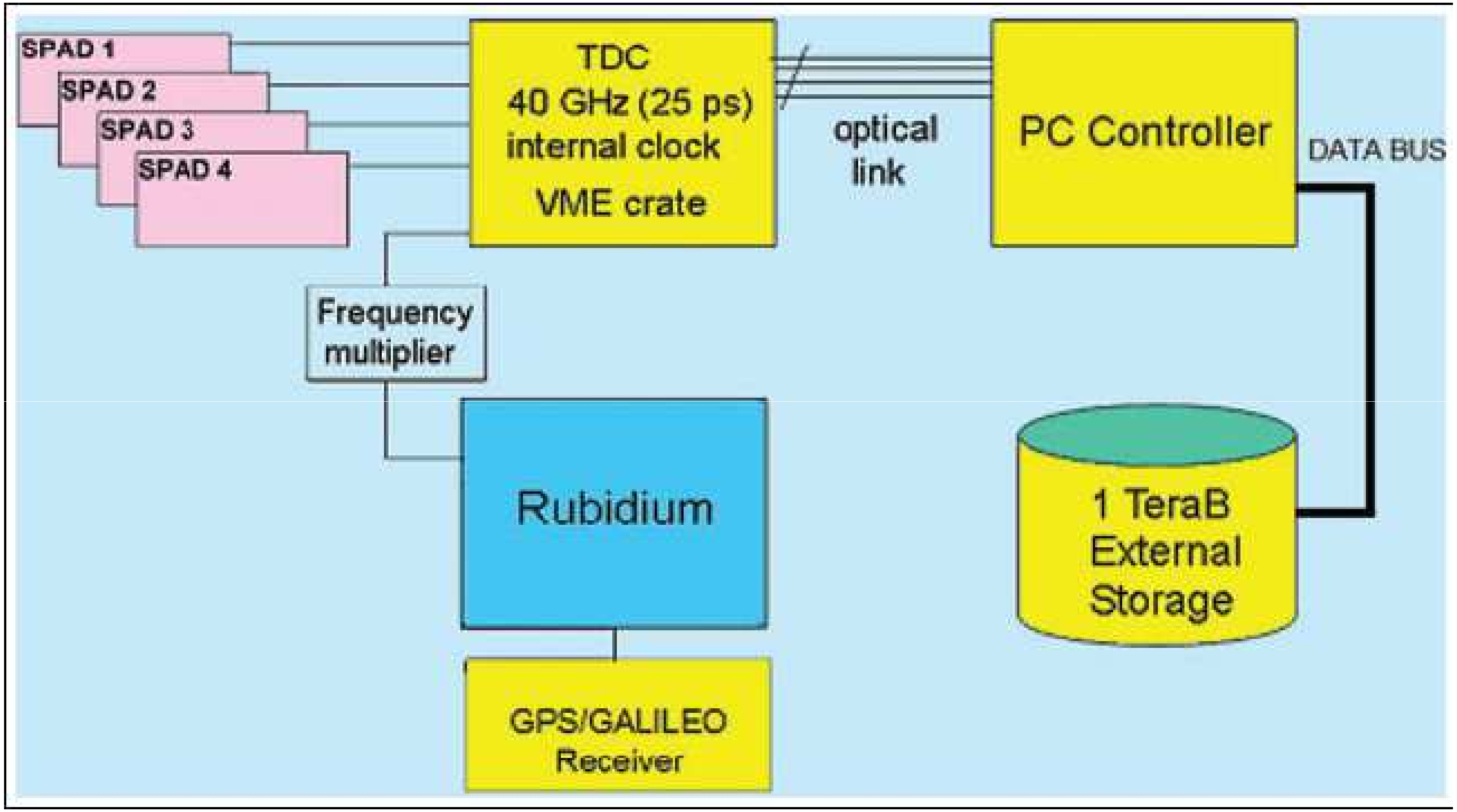
Aqueye dynamic range



Estimated dynamic range of Aqueye, limited on the bright side (V = 5) by the overall performance of the data acquisition system, and by the brightness of the sky background (here calculated for a 3" diameter) on the faint side (V = 18).

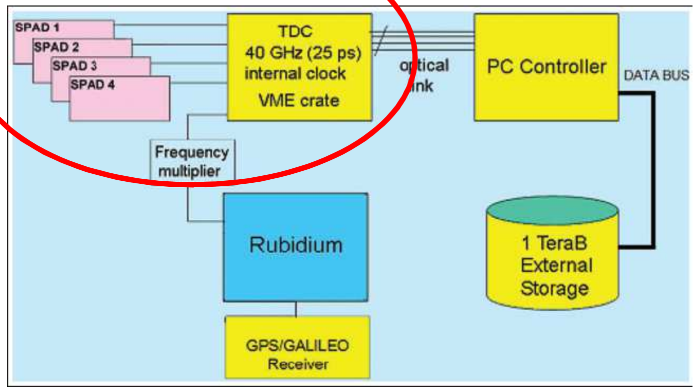
(NB This does not mean it is not possible to detect weaker periodic signals…)

AquEYE electronics schematics



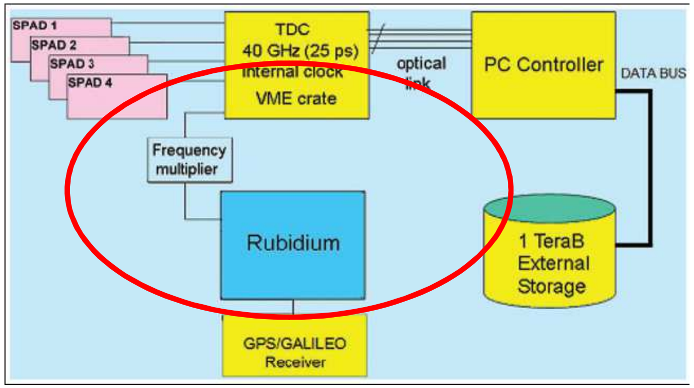
Time tagging

Each SPAD gives as output a very precise (35 ps) NIM signal. Each of the four NIM detector outputs are then connected to a Time-to-Digital (TDC) board where they are time tagged.



The TDC board samples the collected events at 40 GHz (24.414 ps time resolution), multiplying a reference frequency at 40 MHz.

In substitution to the internal 40 MHz quartz oscillator of the TDC unit, not enough accurate/stable for hours of acquisitions, an external frequency reference rubidium oscillator has been used. The rubidium oscillator provides a 10 MHz signal that is multiplied up to 40 MHz through a FPGA electronics to create the main frequency reference of AquEYE.

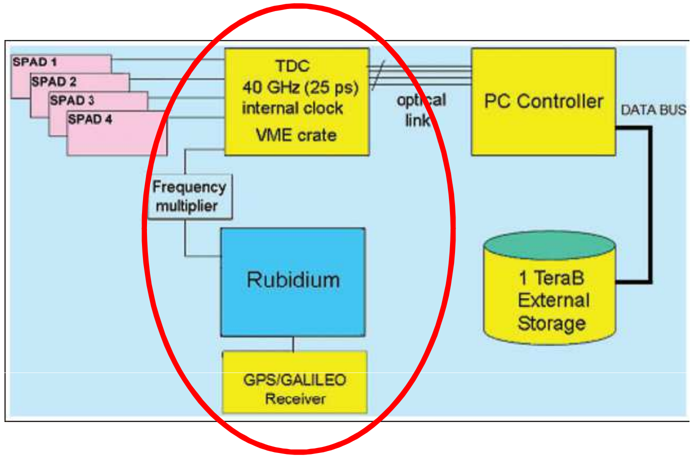


Time referencing

The rubidium clock is extremely accurate on short term, but has a drift for long periods. To remove this drift, the Pulse-per-second (PPS) signal from a GPS receiver is acquired. This PPS has a double function:

a) it provides a signal (the PPS) synchronized within 25 ns rms to UTC: this allows to have an absolute time whose accuracy statistically increases with the integration time (less than 0.5 ns for one hour acquisition)

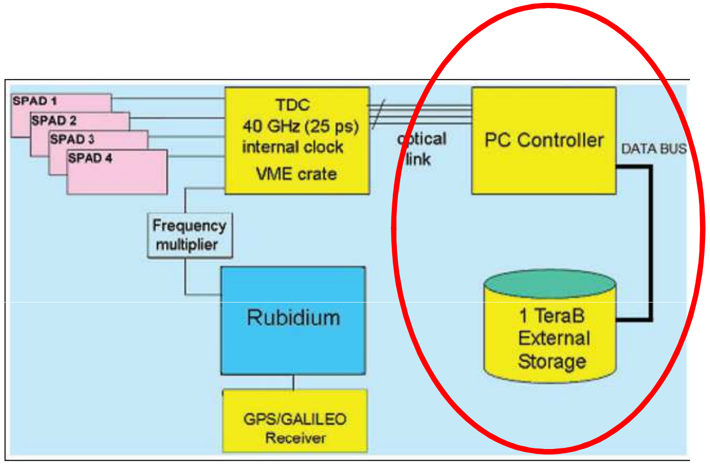
b) by a post-process linear fit analysis of the collected PPS, it is possible to estimate the rubidium drift and remove it. The estimated relative error of the whole timing chain is of the order of 100 ps.



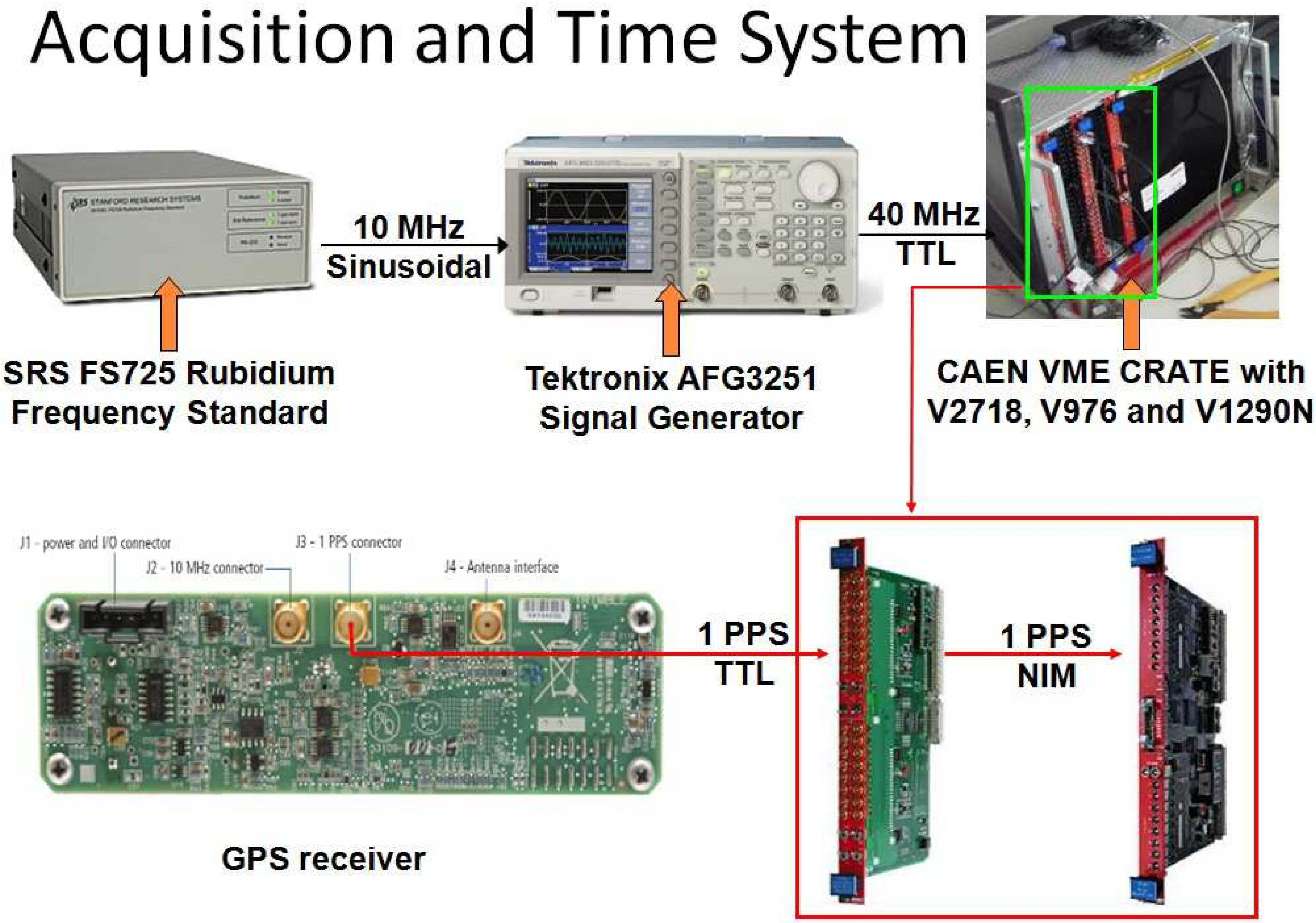
Data handling

The CAEN board is mounted on a VME crate together with an optical bridge. The latter is able to transmit all the VME data traffic in the crate toward a standard PCI board inside the controlling personal computer (PC) with a maximum data-rate of 33 Mbytes/s. Taking in account for the data format, this corresponds to about an 8 MHz maximum count rate, equivalent to a 5th mag star. (NB Brigther stars can anyway be observed, through a neutral density filter).

The acquired data will be temporary stored on the internal hard drives of the PC, for the real time statistical analysis, and then it will be placed on the external 1 TByte hard disk for a permanent storing.



The Aqueye Time & Frequency Unit



Present Aqueye configuration

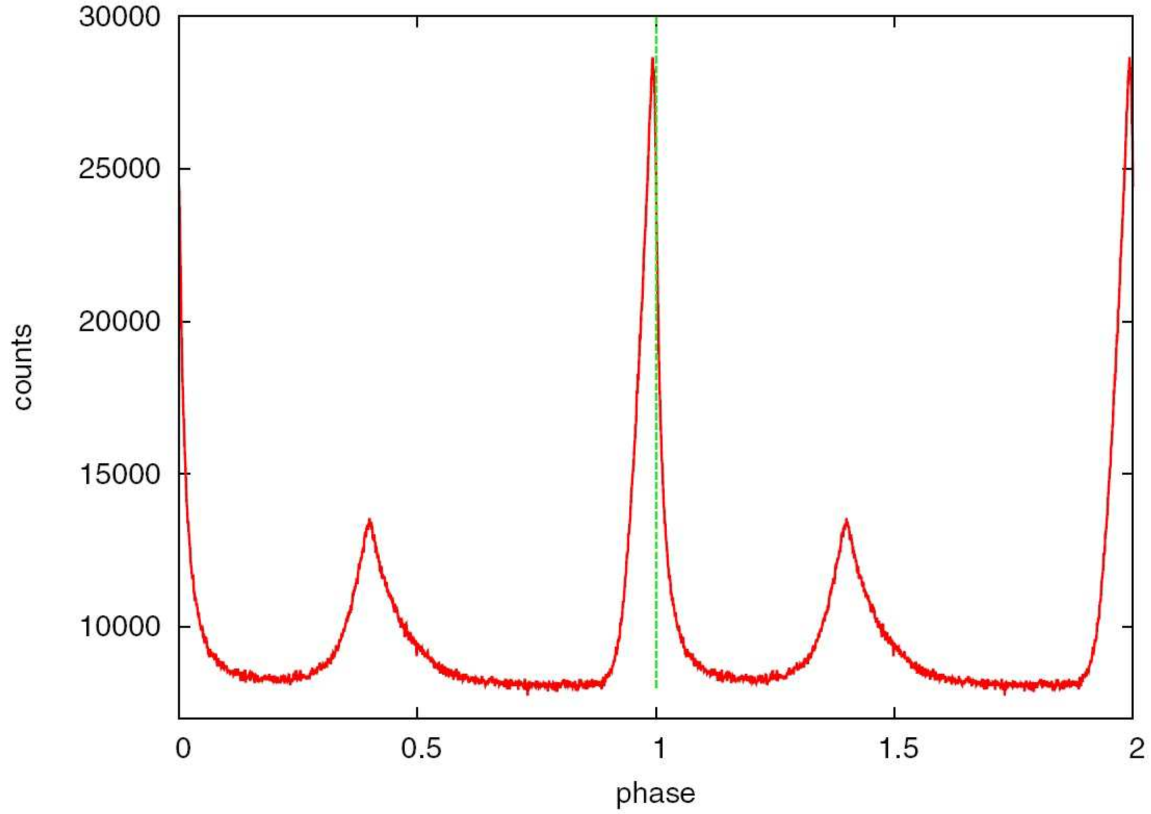
Aqueye presently does not have a pinhole on AFOSC focus, as was initially designed.

Aqueye presently has three SPAD's co-aligned, and one SPAD looking at the closeby sky.

Present SPAD's have a 100 μm diameter sensitive area (already mentioned).

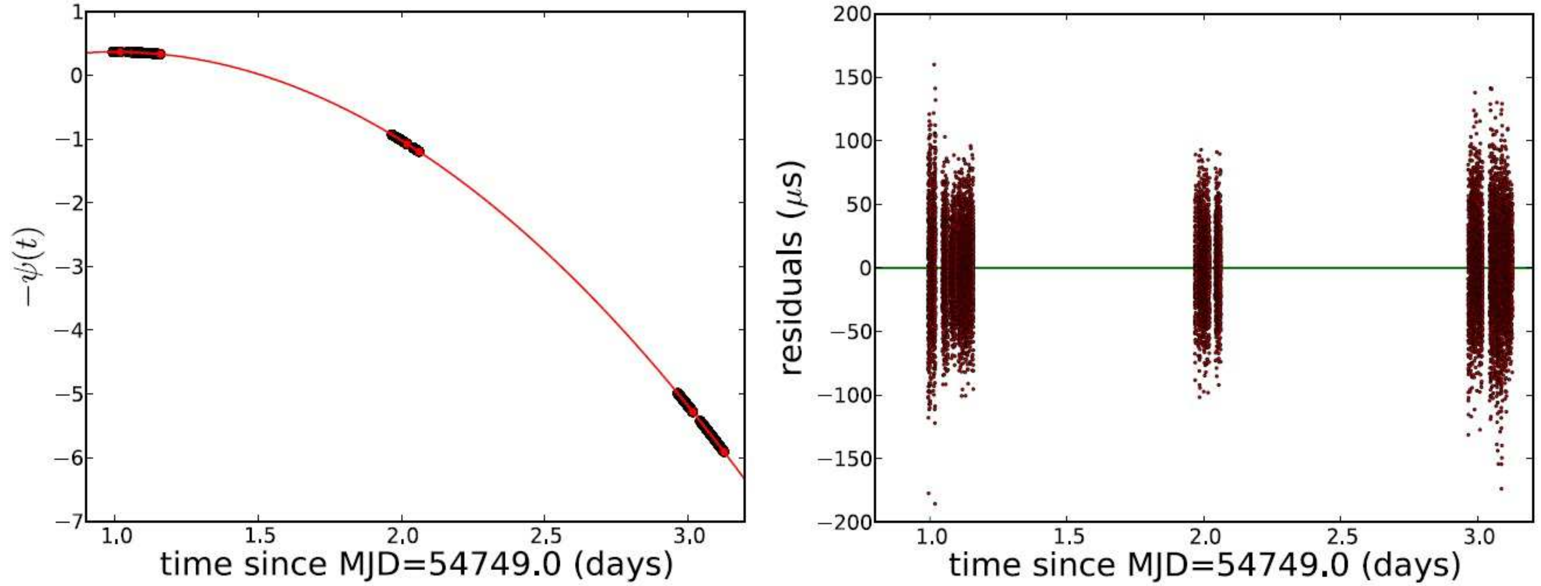
SPAD's have been equipped with heaters (manually controlled).

Some Aqueye results from Crab pulsar (I)



Folded light curve of the Crab pulsar as a function of phase (October 2008). The folding period and the bin time are 0.0336216417 s and 33.6 μs, respectively. Phase zero/one corresponds to the position of the main peak in the radio band and is marked with a vertical *dashed line.*

Some Aqueye results from Crab pulsar (II)



Left: phase drift of the main peak of the Crab pulsar measured during the observing run in Asiago in October 2008. The (red) curve is the best-fitting parabola:

$$\psi(t) = (1.021431 \pm 0.000081) - \left[(3.21329 \pm 0.00011) \times 10^{-5}\,\mathrm{s}^{-1}\right](t - t_0) + \left[(1.859380 \pm 0.000029) \times 10^{-10}\,\mathrm{s}^{-2}\right](t - t_0)^2.$$

The reference epoch t_0 is MJD = 54 749.0, while the reference rotational period is P_{init} = 0.0336216386529 s. Right: phase residuals (in μs) after subtracting the best-fitting parabola from the phase-drift.

Thanks !