First results with AQuEYE, a precursor ‘quantum photometer’ for the E-ELT

C. Barbieri
Department of Astronomy, University of Padova, Italy
cesare.barbieri@unipd.it
Collaborators

The main collaborators are:
- at the Departments of Astronomy, Information Engineering and Mechanics, and Astronomical Observatory

- at the Astronomical Observatories (INAF) in Padova, Cagliari, Catania, Roma and Torino

- at the University of Lund (Sweden), Ljubljana (Slovenia), and Paris (France)

For further information:

http://www.astro.unipd.it/quantumastronomy/
http://abfgroup.com
Our Quantum Optics Activities

We have three main topics of activity connected with applications of Quantum Optics concepts to Astronomy:

- **Statistics of the Photon Stream** from celestial sources, in view of a novel exploitation of the high fluxes provided by the future Extremely Large Telescopes (ELTs).

- **Utilization of the Photon Orbital Angular Momentum (Optical Vorticity)** to achieve super-Rayleigh resolution and a high contrast astronomical coronagraph.

- **Time measurement and distribution** of a very precise time running continuously for hours to distant observers.
The emphasis of this conference will be on **photon statistics studies** in preparation for future Extremely Large Telescopes, including a short discussion of a modern realization of the Hanbury Brown Twiss Intensity Interferometry (HBTII).

Then, I’ll report on the **first tests** of AQuEYE, a **scaled down version of a quantum photometer for the E-ELT**, mounted at the 182-cm telescope in Cima Ekar (Asiago).

Finally, I’ll close with a view of our future plans.
Some Thoughts on Quantum Optics and Astronomy

Photons are very complex entities, carrying more information than extracted in astronomical applications with conventional techniques of imaging, spectroscopy and polarimetry.

According to Glauber, Arecchi, Mandel, etc. seminal papers (from 1963 onwards), arbitrary states of light can be specified as first, second, third and higher order correlation functions with respect to position $r$ and time $t$. 
In 1956 Hanbury Brown and Twiss\textsuperscript{1} reported that the photons of a light beam of narrow spectral width have a tendency to arrive in correlated pairs. We have developed general quantum mechanical methods for the investigation of such correlation effects and shall present here results for the distribution of the number of photons counted in an incoherent beam. The fact that photon correlations are enhanced by narrowing the spectral bandwidth has led to a prediction\textsuperscript{2} of large-scale correlations to be observed in the beam of an optical maser. We shall indicate that this prediction is misleading and follows from an inappropriate model of the maser beam. In considering these problems we shall outline a method of describing the photon field which appears particularly well suited to the discussion of experiments performed with light beams, whether coherent or incoherent.

The correlations observed in the photoionization processes induced by a light beam were given a simple semiclassical explanation by Purcell,\textsuperscript{3} who made use of the methods of microwave noise theory. More recently, a number of papers have been written examining the correlations in considerably greater detail. These papers\textsuperscript{4,5,6,7,8} retain the assumption that the electric field in a light beam can be described as a classical Gaussian stochastic process. In actuality, the behavior of the photon field is considerably more...
Temporal statistics of the photon stream

The *temporal statistics of photon arrival times* gives a measure of ordering (*entropy*) within the photon-stream, and its possible deviations from randomness. Such properties are *reflected in the second- (and higher-) order coherence functions of light, observable as correlations between pairs (or a greater number) of photons*. *Collective properties* of groups of photons cannot be ascribed to any one individual photon. The description of multi-photon phenomena in a photon gas requires a quantum-mechanical treatment, since photons have integer spin, and therefore constitute a *boson fluid with properties different from a fluid of classical distinguishable particles*. The information content lies in the *correlation in time (or space)* between successive photons in the arriving photon stream, and may be significant if the *photon emission process* has involved more than one photon at a time.
PHOTON STATISTICS

Statistics of arrival times in light beams with different entropies. The statistics can be:

- “quantum-random”, as in maximum-entropy black-body radiation (Bose-Einstein distribution) with *bunching* in time

- if the radiation deviates from thermodynamic equilibrium, *anti-bunched* photons may be found, where photons tend to avoid one another;

- in stimulated emission from an *idealized laser*, a uniform photon density is produced.

Adapted from R. Loudon *The Quantum Theory of Light* (2000)
Two photon experiments

Two-photon measurements can be ascribed to quantities of type $I^*I$, i.e. intensity multiplied by itself, which in the quantum limit means observations of pairs of photons, or of statistical two-photon properties.

For $r_1 = r_2$ but $t_1 \neq t_2$ we have an intensity-correlation spectrometer, which measures $\langle I(r,0) \cdot I(r,t) \rangle$, determining the spectral width of the line (see the communication by D. Dravins and C. Germanà).

In the Hanbury Brown Twiss Intensity Interferometer (HBTII) this is measured for $r_1 \neq r_2$ but $t_1 = t_2$: $\langle I(r_1,0) \cdot I(r_2,0) \rangle$, thus deducing angular sizes of stars, reminiscent of a classical interferometer (together with the University of Ljubljana we plan a pilot experiment of a modern realization of the original Narrabri Intensity Interferometer).
The Narrabri Intensity Interferometer

A large Intensity Interferometer was put in operation around 1965 at Narrabri, Australia. Each 6.5m 'mirror' was a mosaic of 252 38-cm hexagonal mirrors. By the end of the decade it had measured the angular diameters of more than 20 blue stars, including main sequence stars.

Notice that there is no optical link (as in Michelson type configuration), only electrical cables and correlation among the two currents. The two telescopes can be arbitrarily distant, a sort of optical VLB Intensity Interferometry.
Future of HBTII with ELTs?

The advantages of the HBTII which in my opinion will survive in the post-VLTI era include:

1- ease of adjusting the time delays of the channels to equality within few centimeters (electronic instead of optical compensation);
2 - immunity to seeing: *adaptive optics is not required*
3 - *blue sensitivity*, with the possibility to utilize the large body of data from Michelson-type interferometers and to supplement their data with observations in this spectral region.
Why Extremely Large Telescopes?

The above mentioned quantum correlations are fully developed on time scales of the order of the *inverse optical bandwidth*. For instance, with the very narrow band pass of 1Å in the visible, through a definite polarization state, typical time scales are \( \approx 10^{-11} \) seconds (10 picoseconds).

However, the photon flux is very weak even from bright stars, so that only the future Extremely Large Telescopes (ELTs) can bring Quantum Optical effects in the astronomical reaches.

*The amplitude of second order functions increases with the square of the telescope area* (not diameter!), so that a 40m telescope will be 256 times more sensitive to such correlations than the existing 10m telescopes.
From micro- to pico-seconds

Expected phenomena below the microsecond frontier are:

- 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
- Quantum statistics of photon arrival times
- Astrophysical laser-line emission (see the paper by D. Dravins and C. Germanà)

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and then the unexpected…
How to reach the shortest temporal domains

On the instrumental side, we need a photon counting photometer running *continuously* for hours, keeping the time tagging capability at the level of 10 picoseconds. With such (ideal) instrument we would achieve two major goals:

- on ELTs, we could perform a direct statistical analysis of the photon stream, with the hope to detect the mentioned second (and higher) order correlation functions
- on two (or more) distant telescopes, we could reproduce a modern version of the Hanbury Brown – Twiss Intensity Interferometry with orders of magnitude improved sensitivity.

Needless to say, such a photometer, mounted even on a smaller telescope, would produce data with an exceptionally high dynamic range.
The QUANTEYE Study

In 2005, we performed a study (QuantEYE, the ESO Quantum Eye) in the frame of the studies for the instrumentation of the 100m OverWhelmingly Large (OWL) telescope.

Although the E-ELT diameter is today around 40m, the QuantEYE study maintains its full validity to set the main design characteristics of an instrument for Astronomy when pushed to its quantum limits.
QuantEYE Optical Design

The optical design was driven by the available single-photon very-high time resolution counters, which at present come as *single units of small dimensions*. Therefore the pupil of OWL had to be divided in a large number of small sub-pupil. The baseline solution was a non-imaging photometer made by a focal reducer plus a 10x10 lenslet array (100 detectors).

At the focus of each lens an optical fiber couples to each single photon detector. The filters are inserted in the parallel beam. A number of very narrow (∼1 Å) bandpass filters, 4 linear polarizers, a number of broad band filters (e.g. BVRI) were considered.
A complete pictorial view of the QuantEYE system

UTC
external clock

This part to be better investigated

Two heads were foreseen, one in axis and one moving on the scientific field to find a comparison star.
To gain experience for such highly unconventional instrument, we have built a prototype of QuantEye, named AQuEye (the Asiago Quantum Eye) for the 182 cm Copernicus Telescope at Asiago - Cima Ekar.
AQuEye on AFOSC

The existing Asiago imaging spectrograph (AFOSC) provides an intermediate pupil of the telescope. Following the QuantEYE design, the pupil of the 182-cm telescope is divided in 4 sub-pupils, and AQuEYE behaves essentially as a fixed aperture (3 arcsec diameter), 4 simultaneous channel, photometer.

AQuEYE is mounted in place of the standard CCD camera of AFOSC, which also takes care of all ancillary functions (shutter, field acquisition and rotation, guiding, controls, etc.).
**AQuEye Detectors**

We have acquired 4 SPADs, 50 micrometer diameter active area, originally developed by Prof. S. Cova in Milano Polytechnic, and built by MPD (in Bolzano).

**Pros:**
- can tolerate full day light,
- are thermoelectrically regulated,
- the dark count is around 50 Hz
- the timing circuit is integrated in the device, and gives a time stamping accuracy better than 50 ps
- relatively cheap

**Cons:**
- Single pixel, small dimensions
- Dead time of $\approx 80$ ns (12 MHz max count rate from each SPAD)
The SPAD QE as measured in Catania

The QE of one of our SPADs measured at Catania Observatory. It exceeds specs, being above 50% from 500 to 600 nm.
The optical design of AQueueye

The AFOSC pupil is sub-divided in 4 sub-apertures by a pyramid, and each of them is imaged on its SPAD by a four lenses objective. The pyramid is custom built, while the lenses are low cost commercial devices.

>85% Encircled Energy inside the pixel

Optical performances very good at all wavelengths from 420 to 750 nm.
The opto-mechanics of AQuEYE
The Time-To-Digital (TDC) board was developed by CAEN for nuclear physics applications at CERN. Each board can handle up to 16 detectors. The maximum count rate is limited to approximately 8 MHz by the available firmware + VME crate + fiber optics links.
Time System

The UTC is acquired at the beginning of the observations, and its pulse per second (pps) disciplines the internal oscillator.

Available at present: Stanford Research Systems Benchtop Rubidium frequency standard model FS725 (PRS10 Rubidium Frequency Standard). Accuracy at shipment: $5 \times 10^{-11}$: it can maintain the 100ps stability for 100 seconds of continuous free-running operation. More advanced (and costly) solutions are under consideration.
The Electronics of AquEYE - 2

This picture shows 3 of the 4 SPADs, the VME crate with the TDC board and the 1 TeraB storage unit. Our system can handle more than 100 SPADs.
Raw output data

Each detector provides a string of time tags whose precision is $\approx 50$ ps (25 from the electronics, 35 from the detector). All these tags are permanently recorded in the external memory. The raw data (photon arrival times) can then be binned in arbitrary time intervals. Notice that time-binning is done a posteriori, and can be varied at will, no information is lost. The strings (available to the astronomer in FITS format) can be analyzed separately for each channel, or as a unique time-ordered sequence.

C.Barbieri, Erevan, August 2007
Laboratory results – Detector dead time

Left: the distribution of time differences in the photon arrival time provides a direct determination of the dead time of each device, in this case 76.2 ns.
Right: the time difference histogram over the 4 channels.
Laboratory results – Laser vs. Fluorescent lamp light

Left: the autocorrelation function of the signal from the He-Ne laser source is flat from the length of the acquired string down to the shortest time scale.
Right: a fluorescent lamp filter shows a clearly wiggling autocorrelation function.
Laboratory results – The power spectrum of the fluorescent lamp light

The Power Spectral Density of the fluorescent lamp clearly shows frequencies at 100, 200, 300, … Hz.
Statistics of photon arrival times

He-Ne laser light, 600 KHz total count rate. Change of distribution curves with increasing time binning, from $10^{-6}$ to $3 \times 10^{-5}$ seconds.
Using the measured SPAD QE, AFOSC efficiency, internal optics and filter transmissions, we derive the following expected count rate at the Zenith, *per channel*:

<table>
<thead>
<tr>
<th>V</th>
<th>Counts/s</th>
<th>Average time between 2 counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$1.38 \times 10^9$</td>
<td>0.73 ns</td>
</tr>
<tr>
<td>5</td>
<td>$1.38 \times 10^7$</td>
<td>73 ns</td>
</tr>
<tr>
<td>10</td>
<td>$1.38 \times 10^5$</td>
<td>730 µs</td>
</tr>
<tr>
<td>15</td>
<td>$1.46 \times 10^3$</td>
<td>0.68 ms</td>
</tr>
<tr>
<td>20</td>
<td>$9.94 \times 10^1$</td>
<td>100 ms</td>
</tr>
</tbody>
</table>
Expected photometric performances -2

Expected performances with the present equipment:

On the bright side:
The limiting factor is the 8 MHz maximum count rate permitted by the electronics (TDC firmware + VME + fiber optics link)

On the faint side:
FoV diameter = 3 arcsec, FoV area = 4.71 (arcsec)$^2$,
Ekar sky brightness: $V = 19$ mag/(arcsec)$^2$,
FoV sky background $V = 17.32$,
SPAD Dark current: 50 c/s, equivalent to a star of $V = 20$,

so that the dark and the sky are equally important to set the limiting factor.

The linear regime then goes approximately from $V = 6.0$ to $V = 18.0$ per channel.
The first light of AquEYE

The first ‘engineering’ photons from sky and stars were acquired at the end of June 2007. We had few more hours (through clouds) the 14th and 15th of August.

AQuEye is mounted so that the shadow and the four spider arms of the secondary correspond to tip and edges of the central pyramid.
The dark counts at the telescope

The darks of the 4 SPADs when mounted at the telescope showed differences larger than the nominal values, with one SPAD 3 times worse, and one 3 times better. Therefore, it is likely that very quiet SPADs can be selected, given time and money.
This is a short section (0.2 seconds), **binned over 280 microseconds**.

The same string, now **binned over 0.01 s**
QR And

300 seconds of data on the ‘polar’ QR And.

Binned over 0.001 seconds

Binned over 1 second
What will be observed with Aqueye?

The 182 cm telescope is too small to detect quantum effects. We plan very high time resolution photometry on different astrophysical problems:

- the mighty Crab pulsar
- Cataclismic variables
- Occultations of stars by KBOs,
- Gamma Ray Bursters,
- timing of exoplanets
- etc.

Atmospheric scintillation over the four 90 cm sub apertures is also in our list.
Plans for the future (2008-2010)

Continue acquisition of astronomical data at the 182-cm telescope

Update the survey for single photon detectors

Update the survey for time availability and distribution

Start joint photon tagging experiment with Ljubljana in preparation for HBTII

Negotiate access to a larger telescope, and design a ‘quantum photometer’ for it (adaptive optics??).
Main References

Dravins et al., 2005, ESO Contract

Dravins 2006, HTRA Book (Galway)

Barbieri et al. 2006, HTRA Book (Galway)

Barbieri et al., 2006, Journal of Modern Optics

Naletto et al. 2007, SPIE Prague

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