First results with AquEYE, the Asiago Quantum Eye

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Our Quantum Optics Activities

Our group has three main topics of activity:

- **Single and entangled photon communications in free space**, over interplanetary distances, for basic physics and quantum communications and cryptography.
- **Utilization of the Photon Orbital Angular Momentum (Optical Vorticity)** to achieve super-Rayleigh resolution and a high contrast astronomical coronagraph.
- **Quantum 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) with apertures from 30 to 50 m.

*Time measurement and distribution* enter in a fundamental way in these topics, so we have a parallel activity on the utilization and dissemination of a very precise time running continuously for hours, inside the **Harrison Project**, supported by the GALILEO Global Navigation Satellite System.
Collaborators

The main collaborators are:
- at the Departments of Astronomy, Information Engineering and Mechanics, and Astronomical Observatory in Padova
- at the Astronomical Observatories in Cagliari, Catania, Roma and Torino
- at the University of Lund (Sweden) and Ljubljana (Slovenia)
- at the University of Vienna (Austria) and Munich (Germany)

but we are surely open to more!
For further information:

http://www.astro.unipd.it/quantumastronomy/
http://abfgroup.com
Subject of this conference

The emphasis of this conference will be on the *photon statistics studies* in view of future Extremely Large Telescopes: after a brief theoretical motivation, I shall report on the *first tests* of a *scaled down version of a quantum photometer*, mounted at the 182-cm telescope in Cima Ekar (Asiago).

Finally, I shall give a short discussion of the problems associated with a modern realization *of the Hanbury Brown Twiss Intensity Interferometry (HBTII)*.
Some Thoughts on Quantum Optics and Astronomy
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.

To elucidate this point, I’ll make recourse to Glauber’s papers (from 1963 onwards), where arbitrary states of light can be specified as first, second, third and higher 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{4-6} 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
Today’s astronomy measures light properties which can be deduced from its 1st order correlation function $G^{(1)}(r, t)$, where $E$ is the amplitude of the electric field, $<>$ indicates the average over time, and * indicates the complex conjugate.
Instruments measuring first-order spatial coherence

Galileo’s telescope (1609)

Hubble Space Telescope (1990)
Instruments measuring first-order temporal coherence

Fraunhofer’s spectroscope (1814)

HARPS (2003) The ESO high resolution spectrograph for extrasolar planets
What is NOT observed in Astronomy - 1

Such measurements cannot distinguish sources with different emission mechanisms but characterized by the same $G(1)$. In other words, light from various sources can be created through different (and typically unknown) physical processes: thermal radiation, stimulated emission, synchrotron radiation, etc. Now, assume one is observing these sources through “filters”, adjusted so that all sources have the same size and shape, same intensity, same spectrum, and the same polarization.

How can one then tell the difference when observing the sources from a great distance?
For sources as defined, it actually is not possible, not even in principle, to segregate them using any classical astronomical instrument:

Telescopes with imaging devices (cameras or interferometers) would record the same spatial image, and any spectrometer would find the same spectrum.

Therefore, two- or multiple photon processes in the source cannot be discriminated, not even in principle, from thermal processes.

Still, the light from those sources can be physically different since photons have more degrees of freedom than those relevant for mere imaging by telescopes or for spectroscopic analysis.
Further properties of the photon stream

However, a photon stream has further degrees of freedom, such as the \textit{temporal statistics of photon arrival times}, giving a measure of ordering (\textit{entropy}) within the photon-stream, and its possible deviations from “randomness”.

Such properties are reflected in the second- (and higher-) order coherence of light, observable as correlations between pairs (or a greater number) of photons.

Clearly, the differences lie in \textit{collective properties} of groups of photons, and cannot be ascribed to any one individual photon. The information content lies in the correlation in time (or space) between successive photons in the arriving photon stream (\textit{or the volume of a “photon gas”}), and may be significant if the photon emission process has involved more than one photon at a time.
In the Hanbury Brown Twiss *Intensity Interferometer* (HBTII) this is measured for \(r_1 \neq r_2\) but \(t_1 = t_2\): \(<I(0,0) I(r,0)>\), thus deducing angular sizes of stars, reminiscent of a classical interferometer. For \(r_1 = r_2\) but \(t_1 \neq t_2\) we instead have an *intensity-correlation spectrometer*, which measures \(<I(0,0) I(0,t)>\), determining the *spectral width* of e.g. scattered laser light.
Multi-photon phenomena

The description of collective 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.

A simplified expression for the second order correlation function with respect to time is:

\[
g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau) \rangle}{\langle I(t) \rangle^2} = g^{(2)}(-\tau)
\]

\[
g^{(2)}(0) = \frac{\langle I(t)I(t) \rangle}{\langle I(t) \rangle^2} = \frac{\Delta I^2}{\langle I(t) \rangle^2} + 1 \geq 1, \quad \frac{\langle I(t)I(t+\tau) \rangle^2}{\langle I(t) \rangle^2 \langle I(t+\tau) \rangle^2} \leq 1
\]

For any classical wave, the degree of coherence \(g^{(2)}(\tau)\) should always be less than \(g^{(2)}(0)\). This result is contradicted for quantum states of light.

Measuring \(g^{(2)}\), it is possible to deduce the atomic energy level populations, which is an example of an astrophysically important parameter (non-LTE departure coefficient) which cannot be directly observed with classical measurements of one-photon properties.
Different statistics for laser gaussian lights

F.T. Arecchi,

PHOTON STATISTICS IN GAUSSIAN AND LASER SOURCES


Laser light does not show the typical bunching of thermal light, it must have $G^{(2)} = 1$, namely a Poisson statistics at any time scale.
Photon correlation spectroscopy

Apparent identical spectral lines might instead have entirely different quantum statistics.


To resolve narrow optical laser emission ($\Delta \nu \approx 10$ MHz) requires spectral resolution $\lambda/\Delta \lambda \approx 10^8$ achievable by photon-correlation spectroscopy (delay time $\Delta t \approx 100$ ns, 20m delay line).
Advantages of photon correlation spectroscopy

Analogous to spatial information from intensity interferometry, photon correlation spectroscopy does not reconstruct the shape of the source spectrum, but “only” gives linewidth information.

**Advantage #1:** Photon correlations are insensitive to wavelength shifts due to local velocities in the laser source.

**Advantage #2:** Narrow emission components have high brightness temperatures, giving higher S/N ratios in intensity interferometry.
Additional Properties

**MULTI-PHOTON PROPERTIES**

- Chaotic light:
  \[ < I^n > = n! < I >^n \]

- Stable wave:
  \[ < I^n > = < I >^n \]

- Chaotic light scattered by Gaussian medium:
  \[ < I^n > = (n!)^2 < I >^n \]

- Anti-bunched light:
  \[ < I^n > = 0 \quad [n \geq 1] \]

*D.Dravins, ESO Messenger 78, 9 (1994)*

Many different quantum states of optical fields exist, not only those mentioned above which can be given classical analogs, but also e.g. **photon anti-bunching** which with \( g^{(2)} = 0 \) is a **purely quantum-mechanical** state. This implies that neighboring photons "avoid" one another in space and time. An anti-bunching tendency implies that the detection of a photon at a given time is followed by a decreased probability to detect another immediately afterward.

For a source with \( g^{(2)} \neq 2 \), **neither an intensity interferometer nor an intensity-correlation spectrometer will yield correct results**. Additional measurements are required to fully extract the information content of light.
Fluorescence Anti-bunching

H. Kimble, M. Dagenais, L. Mandel,

*Photon Antibunching in Resonance Fluorescence*

PHOTON STATISTICS

Statistics of photon arrival times in light beams with different entropies (different degrees of “ordering”). The statistics can be:
- “quantum-random”, as in maximum-entropy black-body radiation (following a Bose-Einstein distribution with a characteristic “bunching” in time; top),
- or may be quite different if the radiation deviates from thermodynamic equilibrium, e.g. for anti-bunched photons (where photons tend to avoid one another; center),
- or a uniform photon density as in stimulated emission from an idealized laser (bottom).

Semi-classical model of light

This is another representation of the same concepts:

(a) constant classical intensity produces photo-electrons with Poisson statistics;

(b) Thermal light results in a compound Poisson process with a Bose-Einstein distribution, and ‘bunching’ of the photo-electrons (adapted from J.C. Dainty).

The characteristic fluctuation timescales are those of the ordinary [first-order] coherence time of light (on order of 10 picoseconds for a 1 nm passband of optical light, but traces of which are detectable also with lower time resolutions).
Time in the astronomical parameters space

Pushing the time resolution towards the limits imposed by Heisenberg's principle might have the same scientific impact of opening a new window.

We might call this new Astronomy with the name of Quantum Astronomy, or also Photonic Astronomy, to reflect the increasing role of the photon in the optical sciences.
All of Astronomy in Time and Frequency

This slide conveys the idea of all of Astronomy in a time–frequency domain, and of the lower limit imposed by Heisenberg principle. Can the realm of quantum phenomena be approached today?
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 1 A (0.1 nm!) 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 16 times more sensitive to such correlations than the existing 10m telescopes.
## Advantages of very large telescopes

<table>
<thead>
<tr>
<th>Telescope diameter</th>
<th>Intensity (&lt;I&gt;)</th>
<th>Second-order correlation (&lt;I^2&gt;)</th>
<th>Fourth-order photon statistics (&lt;I^4&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6 m</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8.2 m</td>
<td>5</td>
<td>27</td>
<td>720</td>
</tr>
<tr>
<td>4 x 8.2 m</td>
<td>21</td>
<td>430</td>
<td>185,000</td>
</tr>
<tr>
<td>50 m</td>
<td>193</td>
<td>37,000</td>
<td>1,385,000,000</td>
</tr>
<tr>
<td>100 m</td>
<td>770</td>
<td>595,000</td>
<td>355,000,000,000</td>
</tr>
</tbody>
</table>

Too bad the 100m OWL has been scaled down to 42 m!
Quantum effects expected in cosmic light

Astrophysical Masers and Lasers are well known in the radio and far infrared domains.

Few examples of possible Lasers in the near IR and optical bands are provided in the following.
10-µm CO2 Laser in Venus, Mars and Earth atmospheres

Vibrational energy states of CO2 and N2 associated with the natural 10.4 µm CO2 laser.


SETI Lasers??

One might even conceive enormous atmospheric CO2 lasers built by alien (very) intelligent civilizations (SETI) ...

...
Early thoughts about lasers in stellar spectra


Outside of thermodynamic equilibrium, the condition may conceivably arise when the value of the integral turns out to be negative. The physical significance of such a result is that energy is emitted rather than absorbed. This energy must be distinguished, however, from that arising in random emissions. The process merely puts energy back into the original beam, as if the atmosphere had a negative opacity. This extreme will probably never occur in practice.


**Abstract:** The radiative transfer equation is written in microscopic form, and from some simplifications on the ratio of occupation numbers for upper and lower level, *a laser action is suggested.*
More refined models

J. Talbot, *Laser Action in Recombining Plasmas*  

Laser effects in Wolf-Rayet, symbiotic stars, and novae

Raman scattered emission bands in the symbiotic star V1016 Cyg

Energy-level diagram for Raman scattering of O VI photons by neutral hydrogen

Raman scattered emission bands

Eta Carinae is one of the most peculiar objects in the southern sky, with an enormous mass loss (10⁻³ M☉/y). Circa 1830, the so called Homunculus nebula was ejected by the star. Observations with HST have identified a gas cloud that acts as a natural ultraviolet laser pumped by UV radiation. The interstellar laser may result from Eta Carinae's violently chaotic eruptions, in which it blasts parts of itself out into space, like an interstellar geyser


17 July 2007

C.Barbieri, Talk at the Dept. of Physics, University of Lecce
Laser Emission in Eta Car - 2

S. Johansson & V. S. Letokhov
Laser Action in a Gas Condensation in the Vicinity of a Hot Star
S. Johansson & V.S. Letokhov:
- Astrophysical lasers operating in optical Fe II lines in stellar ejecta of Eta Carinae
- Possibility of Measuring the Width of Narrow Fe II Astrophysical Laser Lines in the Vicinity of Eta Carinae by means of Brown-Twiss-Townes Heterodyne Correlation Interferometry
The pulsar in the Crab Nebula

The remnant of the Supernova detected in AD 1054 by Chinese astronomers. The Crab pulsar, with a period of 33 ms, is slowing at the rate of about $10^{-8}$ sec per day. Several phenomena remain to be explained, like the nanosecond giant radio bursts.
The ‘giant pulses’ in the Crab pulsar

\[ T_b \geq 5 \times 10^{37} \text{ K}, \]
the highest brightness temperature observed in the Universe.
The dimension of the emitting region cannot be much greater than one meter.

T.H. Hankins, J.S. Kern, J.C. Weatherall, J.A. Eilek
Nanosecond radio bursts from strong plasma turbulence in the Crab pulsar, Nature 422, 141 (2003)
Radio – Optical Correlation

Mean optical “giant” pulse (with error bars) superimposed on the average pulse. Why no radio- optical frequency dispersion?

A. Shearer, B. Stappers, P. O'Connor, A. Golden, R. Strom, M. Redfern, O. Ryan
Enhanced Optical Emission During Crab Giant Radio Pulses
Coherent emission from magnetars

- Pulsar magnetospheres emit in radio; higher plasma density shifts magnetar emission to visual & IR (= optical emission in anomalous X-ray pulsars?)

- Photon arrival statistics (high brightness temperature bursts; episodic sparking events?). Timescales down to nanoseconds suggested (Eichler et al. 2002)
Other possible cosmic lasers: Random and free electron laser emission

A “random laser” of mm-sized spheres glows with laser-like light. Monochromatic flashes are initiated by a few “lucky” photons that remain inside the material for a long time.


A free-electron laser consists of an electron beam propagating through a periodic magnetic field (CRAB Nebula?) The situation is not much different from what occurs in synchrotron radiators, however a lasing effect can be generated when the magnetic field and the radiation combine to produce a beat wave (called a ponderomotive wave) that travels slower than the speed of light and can be in synchronism with the electrons.

The lased light can be of any wavelength from the IR to the UV to the X-rays.
A summary of astrophysical lasers

Methods for amplification in 3- & 4-level astrophysical lasers
(a, b) Raman scattering; (c, d) Pumping light

Masers and lasers in the active medium particle-density vs. medium-dimension diagram.
From milli- to pico-seconds

In summary, the expected phenomena are:

- Millisecond pulsars
- 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
How to reach the shortest temporal domains

On the instrumental side, we need a photon counting photometer running continuously for hours, and 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 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 novel data with an exceptionally high dynamic range limited only by photon statistics.
Our first experience in Matera
Our first string of ‘quantum’ data was obtained with the 1.5m ASI MLRO telescope in Matera, acquiring photons from the bright star Vega, with a time resolution of 300ns (3000 time worst that the present capabilities of Aqueye), through a 3.5 Å wide filter centered at 532 nm. Fluctuations due to seeing are also plainly evident.
The narrow peaks in the power spectrum are most likely due to proper frequencies in the telescope and its control system. To reduce noise, the data were binned in 0.01 second bins.
A first determination of $g^{(2)}$

Second order correlation function of the previous string. This is simply to show that we are ready to perform the $g^{(2)}$ determination as soon as AquEYE is mounted to the telescope.
The QUANTEYE Study
In 2005, we performed a first study (QuantEYE, the ESO Quantum Eye) in the frame of the studies for the 100m Overwhelmingly Large (OWL) telescope.

Our attempt was to cross the several orders of magnitude between current and (optimistically) possible astronomical time resolutions, from the millisecond towards the picosecond region.

Today, the ESO project is oriented toward an European Extremely Large telescope (E-ELT) with a diameter around 40m. However, the QuantEYE study maintains his full validity, and I’ll use it in the rest of the paper to set the borders for data acquisition and analysis problems when Astronomy will be pushed to its quantum limits.
The **baseline** solution of focal reducer plus lenslet array. Each lenslet is an \( f/1 \) system of four square lenses (all spherical surfaces). At the focus of each lens there is an optical fiber coupling to each single photon detector.

The filters are inserted in the parallel beam. A number of very narrow (\( \approx 1 \) A) bandpass filters, 4 linear polarizers, a number of broad band filters (e.g. BVRI) were considered.
‘Quantum’ Photometric capabilities

no time integration allowed
1 A wide filter + 1 linear polarizer,
SPAD QE = 0.4 at 540 nm,
dark = 100 c/s (correspondent to V = 13.9)

<table>
<thead>
<tr>
<th>V</th>
<th>T(2)</th>
<th>T(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>0.02 s</td>
<td>140 s</td>
</tr>
<tr>
<td>12.5</td>
<td>1.63 s</td>
<td>(39 h)</td>
</tr>
<tr>
<td>15.0</td>
<td>163 s</td>
<td></td>
</tr>
<tr>
<td>17.5</td>
<td>4.5 h</td>
<td></td>
</tr>
</tbody>
</table>

T(2), T(3) = indicative observational time needed to detect deviations from Poisson distribution of arrival times of 2 or 3 simultaneous photons.

The Table shows that Quantum Astronomy is really photon starved!
‘Normal’ Photometric capabilities

a-posteriori time integration allowed
200 A wide filter, SPAD QE = 0.4 at 540 nm, no linear polarizer, dark = 100 c/s, sky V = 20 mag/(arcsec)^2

<table>
<thead>
<tr>
<th>V</th>
<th>S/N = 100</th>
<th>S/N = 10</th>
<th>S/N = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>1 µs</td>
<td>10 ns</td>
<td>1 ns</td>
</tr>
<tr>
<td>10.0</td>
<td>100 µs</td>
<td>1 µs</td>
<td>100 ns</td>
</tr>
<tr>
<td>15.0</td>
<td>10 ms</td>
<td>100 µs</td>
<td>10 µs</td>
</tr>
<tr>
<td>20.0</td>
<td>4 s</td>
<td>40 ms</td>
<td>4 ms</td>
</tr>
<tr>
<td>25.0</td>
<td>3 h</td>
<td>100 s</td>
<td>10 s</td>
</tr>
<tr>
<td>27.5</td>
<td>3 h</td>
<td>1000 s</td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td>&gt;10 h</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Exposure time needed to achieve a given S/N.

QuantEYE has a tremendous dynamic range, from the 5th to the 29th magnitude, better than any other astronomical instrument.
High level data acquisition system

Even without compression, the amount of data can be handled by present-day technology. As extreme example, a run of 1 minute at 1 GHz produces 3 TBytes per head; existing hard drives of 300 GBytes for each of the 25 lines insure two such runs before reading out the data.

An on-line correlator allows real time control of the observation.

The arrival time of each photon in each channel is acquired and stored. An asynchronous post processing guarantees data integrity for future scientific investigation.
Time Generation and Distribution

The optimal *internal* clock for our peculiar application was (and to a certain extent still is) under investigation. We consider different possibilities (from H-Maser to high-quality thermostated quartz).

Regarding the external clock, a UTC receiver (GPS, or Galileo Navigation System when available, or other receivers) sets a time start/stop reference to each observing run, with an absolute precision of +/- 50 ns.
A complete pictorial view of the QuantEYE system
AquEYE
the little brother of
QuantEYE
AQUEYE

The little brother of QuantEYE, named Aqueye (the Asiago Quantum Eye) has been built for the 182 cm Copernicus Telescope at Cima Ekar with very limited resources. We are making the best use of the existing AFOSC imaging spectrograph, which already provides an intermediate pupil.
AquEYE is mounted in place of the standard CCD camera of the Asiago imaging spectrograph (AFOSC). AFOSC takes care of all ancillary functions (field acquisition and rotation, guiding, controls, etc.).
We have concentrated our attention on the Single Photon Avalanche Photodiode (SPAD), originally developed by S. Cova in Milano Polytechnic, built by MPD (in Bolzano) and already used in several AdOpt devices in Italy and at ESO.

Four SPADs have been acquired. The active area is 50 micrometers, the dead time around 80 ns, the dark count less than 50 Hz.
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 Aqueye - 1

The AFOSC pupil is sub-divided in 4 sub-apertures by a pyramid, and each of them imaged on its SPAD by a four lenses objective. The lenses are low cost commercial devices. The pyramid is custom built.
The optical design of Aqueye - 2

Optical performances are very good at all wavelengths from 420 to 750 nm.
The mechanics of AquEYE

In the parallel section of the beam inside each objective, broad band or narrow band filters can be inserted. On the right, AquEYE being aligned on the optical bench.
Electronics with commercial boards

Max SPAD output rate = 10 MHz
SPAD timing jitter = ±35 ps

Under Investigation
(at moment we have a good quality Rubidium, see later)

The selected commercial boards are used in nuclear physics applications.

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The Electronics of AquEYE

This picture shows 3 of the 4 SPADs, the VME crate with the TDC board and the 1 TeraB storage unit.
The UTC is acquired at the beginning and end of the observations, and its pps disciplines the internal oscillator.
Order June 2007

STANFORD RESEARCH SYSTEMS: Benchtop Rubidium frequency standard model FS725 (PRS10 Rubidium Frequency Standard)

accuracy at shipment $5 \times 10^{-11}$: it should maintain the 100ps stability for 100 seconds of continuous free-running operation
Measurements in Cagliari July 2007

July 2007 - Characterization Activities in Cagliari

![Diagram of characterization activities in Cagliari]
What can be observed with Aqueye?

The 182 cm telescope is too small to detect quantum effects, however we can try very high time resolution photometry on different astrophysical problems, starting of course with the mighty Crab pulsar. Occultations and Gamma Ray Bursters are other possible programs, but many more can be thought of.
Atmospheric Scintillation

Adapted from Dravins et al.,
The first light of AquEYE - 1

The first ‘engineering’ photons have been acquired at the end of June 2007.
Each detector provides a string of time tags whose precision is of the order of 50 ps (25 from the electronics, 35 from the detector).
The 4 channels, binned over 85 milliseconds, left on dark, right on sky. One of the SPAD (Channel 2) was obviously much noisier. It has been already replaced. Notice though that the sky is clearly seen above the dark.
The first light of AquEYE – SS Cyg 1

The sum of the 4 channels. This is a short section, binned over 280 microseconds, of a very long string acquired on the variable star SS Cyg (a dwarf Nova, Cataclismic Variable, close binary star).

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The first light of AquEYE – SS Cyg 2

A longer section of the same string, now *binned over 85 ms*, to be more reminiscent of conventional astronomical photometry. Seeing and guiding fluctuations are plainly visible. A new fast TV camera with 16 bit resolution for guiding is being acquired, to have a record of the low frequency (< 4 Hz) intensity fluctuations of the guiding star.

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Cross-correlation of 2 channels – SS Cyg

Cross Correlation of Ch.1 and Ch.2 of SS Cyg binned over 280 microseconds. The value is essentially constant until 0.1 seconds, when seeing fluctuations start decorrelating the two channels.
Hanbury Brown Twiss Intensity Interferometry

(HBTII)
L’Interferometro di Intensità HBTII a Narrabri

I collettori di luce con diametro complessivo di 6.5 m, erano composti da esagoni di 38 cm costruiti dalle Officine Galileo a Firenze. La qualità ottica era piuttosto scadente.

Si notino i due fotomoltiplicatori nei due fuochi primari.

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Il correlatore

Dopo un filtro blu, la luce incideva su due fotomoltiplicatori RCA Type 8575, con fotocatodo di 42 mm (l’immagine stellare era di ben 25 mm).

La fotocorrente era inviata a un amplificatore a larga banda, poi a un phase-reversing switch, e poi a un filtro a larga banda (10-110 MHz). I segnali dai due fotomoltiplicatori erano poi moltiplicati nel correlatore.

Ovviamente, tutto era fatto in modo puramente analogico.
Signal processing

La banda passante elettrica di 100 MHz implica *cammini del segnale uguali a meglio del nanosecondo*, per non perdere in coerenza temporale. Dato che 1ns è circa 30cm, questo requisito non è difficile, e in ogni caso *molto più facile che negli interferometri di fase* (Michelson, Fresnel) dove si richiede la frazione di lunghezza d’onda visibile. Inoltre, questa banda passante esclude gli effetti della turbolenza atmosferica.

E’ interessante ricordare che l’esperimento di Narrabri non rivelo’ alcun effetto avverso dovuto alla radiazione Cherenkov dai raggi cosmici (che si temevano sorgente di rumore altamente correlato).
Risultati di HBTII

La correlazione così misurata è proporzionale a $<\Delta I_1 \Delta I_2>$, dove $\Delta I = I - I_{av}$ è la fluttuazione di $I$ (statistica di Bose Einstein). Si può anche dimostrare che tale correlazione è proporzionale a $|\gamma_{12}|^2$, cioè al quadrato della più familiare visibilità di frangia nell'interferometro di Michelson. Dunque è possibile misurare il diametro della stella, e dal secondo lobo (con sufficiente S/N) anche l'oscuramento al bordo.

CHANGE OF CORRELATION WITH BASELINE (a) Beta Cru (B0 IV); (b) Alpha Eri (B5 IV); (c) Alpha Car (F0 II).
Il rapporto Segnale-Rumore e la temperatura stellare

Il rapporto S/R della tecnica HBTI aumenta molto rapidamente con la temperatura della stella.

Fig.5 Variazione del rapporto segnale/rumore in funzione della temperatura della sorgente per i parametri elettrici e ottici dell’interferometro di intensità costruito a Narrabri, Australia.
Miglioramento atteso con la versione moderna della HBTII

Telescopi di maggiori dimensioni e di migliore qualità ottica, la attuale elettronica digitale, rivelatori di maggior efficienza quantica, possono dare un forte aumento di prestazioni.

Regarding the HBTI with ELTs arrays, see the two papers by A. Ofir e E. Ribak, MNRAS 2006.

\[ \frac{S}{N} = K_{instr} \times QE \times AreaTelescope \times \sqrt{CountBandwidth} \times \sqrt{T} \]
C’è un futuro per la HBTII?

Quali vantaggi può offrire oggi HBTII, nonostante la sua bassa sensibilità (bassa perché effetto al secondo ordine), rispetto agli esistenti interferometri alla Michelson e alla Fresnel, ad es. il VLTI dell’ESO?

Secondo noi sono:
1- la facilità di aggiustare i ritardi temporali elettronicamente e non otticamente (millimetri, non frazioni di lunghezza d’onda!)
2 – immunità al seeing: non serve l’ottica adattiva
3 – sensibilità al blu, con la possibilità di complementare il grande corpo di dati che provengono dagli altri interferometri nel vicino infrarosso, e quindi con la determinazione dei diametri e dell’oscuramento al bordo in funzione della lunghezza d’onda.
Very Long Baseline Optical Intensity Interferometry

Ma lo sviluppo più eccitante potrebbe essere la capacità di fare interferometria con telescopi molto distanti, dato che non c’è la necessità ne’ di un collegamento ottico ne’ di mantenere la fase ottica!
Basta avere un riferimento di tempo comune a meglio di 100 picosecondi, e tenere in considerazione la rifrazione differenziale tra due telescopi.
Questo esperimento si potrebbe fare al più presto con telescopi esistenti, se avessimo un tale riferimento di tempo.
Abbiamo pertanto avviato un esperimento pilota con l’Università di Lubiana (circa 300 km a Est di Asiago).
Distribuzione del tempo tra due telescopi distanti

- Ora, è vero che l’esistente GPS, e probabilmente anche il futuro GNSS non danno la precisione richiesta per tutto il tempo necessario all’esperimento astronomico (a livello di ± 10 ps per alcune ore).
- Tuttavia ci aspettiamo che le esigenze di tante altre discipline, dalla geodesia alle telecomunicazioni, produrranno presto un sensibile miglioramento della situazione.
- Abbiamo ottenuto un contratto (con capofila Alcatel Alenia Space) dal Galileo Joint Undertaking per valutare le applicazioni astronomiche del tempo distribuito dal GNSS. Tale progetto si chiama Harrison, e vi partecipano anche l’Università di Lubjana e l’INAF (Padova, Torino).
Distribuzione di un tempo preciso

Un sistema proposto dall’ ESA e dalla Carlo Gavazzi Space ESA Pat. 407). Basta un solo master clock al suolo e satelliti ripetitori geostazionari (come ASTRA, o EUTELSAT).

Ci sono anche proposte per una distribuzione non radio, ma via laser (sia in Francia che in Cina).
DREAMS
FOR
THE FUTURE
Prototypes for VLT and LBT?

We could develop a scaled-down version of the QuantEYE baseline for the Nasmyth focus of the VLT (one focal station being available at Melipal for visitor instruments).

(Using a collimator having a focal length of 400mm, we have a 30mm diameter parallel beam which can be intercepted by a 3x3 lenslet array. Each lens is a square of 10x10mm. With 30mm focal length (f/3) one gets a 40 µm spot, well inside a 50 µm SPAD).

An imaging solution is also possible with (a difficult to build, but not impossible) lenslet arrays and 30x30 detectors. Another attractive possibility would be to go to the large room where the light from the 4 telescopes are brought together before entering the VLTI proper, to perform HBTI.

LBT would provide another very important test bench, in particular for HBTII.
MAGIC as a ELT precursor

The Air Shower Cherenkov Light Collector MAGIC, just below the TNG on the Roque. The central pixel of the prime focus camera is empty and can be used for optical work. The total aperture is 17m, and the PSF is approximately 3 arcmin (better than the original Narrabri realization).

Moreover, a second collector, of much superior optical quality, in particular regarding isochronism, is in construction 100m away.
More in the future: clock synchro by means of entangled photons?

Weinfurter, Zeilinger, Rarity, Barbieri, Project QIPS (ESA)