TOWARDS A SQUARE-KILOMETER OPTICAL TELESCOPE: Digital Revival of Intensity Interferometry

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“Make no small plans
Dream no small dreams”

George Ellery Hale
(1868-1938)
CTA, Cherenkov Telescope Array 2017?
Narrabri observatory with its circular railway track

Flux collectors at Narrabri

R.Hanbury Brown: The Stellar Interferometer at Narrabri Observatory
Sky and Telescope 28, No.2, 64, August 1964
Intensity interferometry

PHOTON CORRELATIONS*

Roy J. Glauber
Lyman Laboratory, Harvard University, Cambridge, Massachusetts
(Received 27 December 1962)

In 1956 Hanbury Brown and Twiss\(^1\) 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\(^2\) 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,\(^3\) 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\(^2,4-6\) 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
PHOTON STATISTICS

Top: Bunched photons (Bose-Einstein; 'quantum-random')
Center: Antibunched photons (like fermions)
Bottom: Coherent and uniformly spaced (like ideal laser)

Roy Glauber
Nobel prize in physics
Stockholm, December 2005

“For his contribution to the quantum theory of optical coherence”
TWO-PHOTON EXPERIMENTS

2:nd order correlation function:

\[ G^{(2)}[r_1, t_1; r_2, t_2] = \langle I(r_1, t_1) I(r_2, t_2) \rangle \]

Special case: \( r_1 = r_2, t_1 = t_2 \)

\[ \langle I(0,0) I(0,0) \rangle \quad \text{"QUANTUM SPECTROMETER"} \]

Special case: \( r_1 \neq r_2, t_1 = t_2 \)

\[ \langle I(0,0) I(r,0) \rangle \quad \text{"INTENSITY INTERFEROMETER"} \]

Special case: \( r_1 = r_2, t_1 \neq t_2 \)

\[ \langle I(0,0) I(0,t) \rangle \quad \text{"CORRELATION SPECTROMETER"} \]
Intensity interferometry

**Pro:** Time resolution of 1 ns implies 30 cm light travel time; no need for any more accurate optics nor atmosphere. Short wavelengths no problem; hot sources observable

**Con:** Signal comes from two-photon correlations, increases as signal squared; requires large flux collectors
John Davis & Robert Hanbury Brown with model of a proposed very large stellar intensity interferometer with 12 m flux collectors, spanning a 2 km baseline

Model of the once proposed very large stellar intensity interferometer, spanning a 2 km baseline (J. Davis & R. Hanbury Brown)
Sic transit gloria mundi...

Motel restaurant and bar in Narrabri, its wall covered with mirrors from the former observatory.

Photos: D. Dravins
Digital intensity interferometry

Very fast digital detectors, very fast digital signal handling, and the quantum-optical theory of optical coherence now enable very-long-baseline optical interferometry by combining distant telescopes in software.
• Other instruments cover seconds and milliseconds
• QuantEYE will cover milli-, micro-, and nanoseconds, down to the quantum limit!
High time-resolution astrophysics & Intensity interferometry

Iqueue instrument @ NTT on La Silla, January 2009

Padova team: Ivan Capraro, Paolo Zoccarato, Andrea di Paola, Cesare Barbieri, Enrico Verroi, Tommaso Occhipinti, Giampiero Naletto
Skinakas Observatory, Crete

The *OPTIMA* instrument (*Optical Pulsar TIMing Analyzer*) of the Max-Planck-Institute for Extraterrestrial Physics (Garching), mounted at the Cassegrain focus of a 1.3 m telescope.
Autocorrelation functions of the Crab pulsar, measured by photon-counting avalanche photodiodes in the OPTIMA instrument, computed by a real-time digital signal correlator of QVANTOS Mark II (Lund Observatory). The rise below 1 µs is due to detector afterpulsing.
Digital Intensity Interferometry

Laboratory setup at Lund Observatory
AIR CHERENKOV TELESCOPES

VERITAS

MAGIC

H.E.S.S.

CANGAROO III
Steps towards a km$^2$ optical telescope

Full-scale test observations with VERITAS, Oct. 2007

Dainis Dravins (Lund Observatory)
Stephan LeBohec (University of Utah)
Michael Daniel (University of Leeds)

Digitally correlated pairs of 12-meter telescopes

* Photon rates > 30 MHz per telescope
* Real-time cross correlation, $\Delta t = 1.6 \text{ ns}$
The four 12-meter telescopes of the VERITAS array in Arizona offer baselines between 34-109 m
S.LeBohec, M.Daniel, W.J.de Wit, J.A.Hinton, E.Jose, J.A.Holder, J.Smith, R.J.White
Stellar Intensity Interferometry with Air Cherenkov Telescope Arrays
Intensity interferometry can be carried out in moonlight when Cherenkov observations are not feasible.
CTA, Cherenkov Telescope Array
An advanced facility for ground-based gamma-ray astronomy
Left: Distribution of interferometer baselines in one possible large-scale array of 81 telescopes placed in a 1 km² square grid with 125 m spacing. The upper scale indicates the baseline for the first interferometric minimum for a uniform stellar disk observed at 350 nm.
Right: The two-dimensional baseline distribution, with scales in meters.

S.LeBohec, M.Daniel, W.J.de Wit, J.Hinton, E.Jose, J.A.Holder, J.Smith, R.J.White: Stellar Intensity Interferometry with Air Cherenkov Telescope Arrays, AIP Conf. 984, 205 (2008);
Figure 1. **Left:** $|\gamma_d|^2$ as a function of baseline for three different stellar angular diameters. The vertical lines indicate the two baselines available to VERITAS. **Right:** Visual magnitude angular diameter relationship for the main sequence, the giant and the super-giant branches for distances of 3 pc, 30 pc and 300 pc.

S. LeBohec, J. Holder

*Using Atmospheric Cherenkov Telescope Arrays as Intensity Interferometers*

For stars with the same angular diameter but decreasing temperatures (thus decreasing fluxes), telescope diameter must successively increase to maintain the same S/N.

When the mirrors become so large that the star is resolved by a single mirror, the S/N drops.

For stars cooler than a given temperature, no gain results from larger mirrors.

Mirror diameter needed to achieve $S/N = 3$ in 1h, 2h, or 3h, at a given $V$ magnitude, assuming a QE of 0.4 and an electrical bandwidth of 10 GHz. The inset expands the curve to show the capabilities of VLT and LBT, and of MAGIC. The HBT arrow indicates the limiting magnitude achieved by the original Narrabri interferometer. $S/N$ denotes the excess counts of intensity fluctuations over the fluctuations of the random coincidences.
S/N RATIO IN INTENSITY INTERFEROMETRY

is proportional to:

- Detector quantum efficiency
- Effective telescope area $A$ \[\text{actually } \sqrt{A_1 \times A_2}\]
- Photon flux per unit frequency bandwidth
- Square root of the integration time
- Square root of the electronic bandwidth

is independent of

- Width of spectral passband
H. Jensen: *Hot stars as targets for intensity interferometry*,
presented at the workshop on Stellar Intensity Interferometry, Salt Lake City, January 2009
Examples of exceptional stars as prime candidate targets for intensity interferometry.

H. Jensen: *Hot stars as targets for intensity interferometry*, presented at the workshop on Stellar Intensity Interferometry, Salt Lake City, January 2009
P. Nuñez, S. Le Bohec, D. Kieda, R. Holmes: Image Recovery in Intensity Interferometry, presented at the workshop on Stellar Intensity Interferometry, Salt Lake City, January 2009
Images reconstructed from simulated (noiseless) intensity interferometer data at \(\approx 400\) nm, for an array with 100 telescopes separated by \(\approx 100\) m. Pristine images are at top left.

The images were produced using an algorithm based on the Cauchy-Riemann equations; for an earlier one-dimensional version of this, see Holmes & Belen'kii, *JOSA A* 21, 697 (2004).

Images reconstructed from simulated (noiseless) intensity interferometer data at ≈ 400 nm, for an array with 100 telescopes separated by ≈ 100m. Pristine images are at top left.

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P.Nuñez, S.Le Bohec, D.Kieda, R.Holmes: Image Recovery in Intensity Interferometry, presented at the workshop on Stellar Intensity Interferometry, Salt Lake City, January 2009
Investigation of the Cauchy–Riemann equations for one-dimensional image recovery in intensity interferometry

R. B. Holmes

Nutronics, Inc., 3357 Chasen Drive, Cameron Park, California 95682

Mikhail S. Belen’kii

Trex Enterprises, 10455 Pacific Center Court, San Diego, California 92121

Received September 22, 2003; accepted December 17, 2003

A method of image recovery using noniterative phase retrieval is proposed and investigated by simulation. This method adapts the Cauchy–Riemann equations to evaluate derivatives of phase based on derivatives of magnitude. The noise sensitivity of the approach is reduced by employing a least-mean-squares fit. This method uses the analytic properties of the Fourier transform of an object, the magnitude of which is measured with an intensity interferometer. The solution exhibits the degree of nonuniqueness expected from root-flipping arguments for the one-dimensional case, but a simple assumption that restricts translational ambiguity also restricts the space of solutions and permits essentially perfect reconstructions for a number of nonsymmetric one-dimensional objects of interest. Very good reconstructions are obtained for a large fraction of random objects, within an overall image flip, which may be acceptable in many applications. Results for the retrieved phase and recovered images are presented for some one-dimensional objects and for different noise levels. Extensions to objects of two dimensions are discussed. Requirements for signal-to-noise ratio are derived for intensity interferometry with use of the proposed processing. © 2004 Optical Society of America
Flat-top object and its reconstruction:
(a) true (black) and reconstructed (gray);
(b) magnitude of the Fourier transform of the object;
(c) true (black) and reconstructed (gray) phase of the Fourier transform of the object.

ASTRONET Infrastructure Roadmap

http://www.astronet-eu.org/

For the section on High-Energy Astrophysics, Astroparticle Physics and Gravitational Waves, highest-priority near-term (~2015) project is CTA; in overall list is 2nd highest priority among medium-scale ground-based projects (following the European Solar Telescope).

ESFRI, European Strategy Forum on Research Infrastructures


Eight prioritized projects within Physical Sciences and Engineering, include CTA

ASPERA network on astroparticle physics

http://www.aspera-eu.org/

The priority project for VHE gamma astrophysics is the Cherenkov Telescope Array, CTA.
Cherenkov Telescope Array

www.cta-observatory.org

The *CTA Design Study* is to optimize the planned observatory

Primary targets are to constrain design and technology options;
*Optimize the cost/performance ratio;*
*Define how CTA is to be constructed and operated;*
*Build and test prototype telescope(s)*
**CTA CONSORTIUM DESIGN STUDY**

Approximately four years, 2008-2011

11 work packages

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
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<tbody>
<tr>
<td>PHYS</td>
<td>Astrophysics and astroparticle physics</td>
</tr>
<tr>
<td>MC</td>
<td>Optimization of array layout, performance studies and analysis algorithms [MonteCarlo]</td>
</tr>
<tr>
<td>SITE</td>
<td>Site evaluation and site infrastructure</td>
</tr>
<tr>
<td>MIR</td>
<td>Design of telescope optics and mirror</td>
</tr>
<tr>
<td>TEL</td>
<td>Design of telescope structure, drive and control systems</td>
</tr>
<tr>
<td>FPI</td>
<td>Focal Plane Instrumentation</td>
</tr>
<tr>
<td>ELEC</td>
<td>Readout electronics and trigger</td>
</tr>
<tr>
<td>ATAC</td>
<td>Atmospheric monitoring, associated science and instrument calibration</td>
</tr>
<tr>
<td>OBS</td>
<td>Observatory operation and access</td>
</tr>
<tr>
<td>DATA</td>
<td>Data handling, processing, management and data access</td>
</tr>
<tr>
<td>QA</td>
<td>Risk assessment and quality assurance</td>
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</tbody>
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PHYSICS WORK PACKAGE

Work Package Coordinator: Diego F. Torres
ICREA & Institut de Ciencies de l’Espai (IEEC-CSIC), Barcelona, Spain

Physics WP topics & Task Leaders

Dark matter / Fundamental physics — Jan Conrad
Extragalactic background light / Cosmology — Daniel Mazin
AGNs — Helene Sol, Catherine Boisson, Andreas Zech
Cosmic rays / Clusters / Starbursts — Olaf Reimer
Microquasars / Binaries — Josep M. Paredes
Cosmic rays / SNRs / Molecular clouds — Stefano Gabici
Pulsar-wind nebulae — Okkie de Jager
Pulsars / Globular clusters — Bronek Rudak
Galactic center — Stefan Funk
Multi-wavelength / Transients / GRBs — Sera Markoff
Timing — Dimitri Emmanoulopoulos
Surveys / Sub-arrays — Guillaume Dubus
Extended / Diffuse Sources — Sabrina Casanova
Intensity Interferometry — Dainis Dravins
Direct-Cherenkov light / CR composition — Rolf Bühler
CTA desiderata

Isochronous telescope design?

Parabolic or Schmidt better than Davies-Cotton for $\Delta t < \text{few ns}$
Cherenkov telescopes are usually Davies-Cotton or parabolic.

In a Davies-Cotton layout, all reflector facets have same focal length $f$, arranged on a sphere of radius $f$.

In a parabolic layout, mirrors are arranged on a paraboloid, and the focal length of the (usually spherical) mirror facets varies with the distance from the optical axis.

Both have significant aberrations off the optical axis, the parabolic slightly worse than Davies-Cotton.

Time dispersion introduced by the reflector should not exceed the intrinsic spread of the Cherenkov wavefront of a few ns.

Parabolic reflectors are isochronal – apart from minute effects caused by individual mirror facets being spherical rather than parabolic.

Davies-Cotton layout causes a spread of photon arrival times at the camera; a plane incident wavefront results in photons spread over $\Delta t \approx 5$ ns, with an rms width $\approx 1.4$ ns.
Parabolic reflector of MAGIC I, Roque de los Muchachos, La Palma. Its isochronous reflector has an intrinsic time spread of only 400 ps, sufficient to resolve the time structure of the cosmic showers.
INTRINSIC TIME SPREAD IN 20 m Ø CHERENKOV TELESCOPE

Top: Spherical (Davies-Cotton)

A spherical reflector substantially widens the photon pulse.

At detecting 10 GeV γ-showers, the pulse width on the spherical telescope's focal plane may reach 15-20 ns instead of the inherent 5-8 ns.

Angles of incidence = 2°

Bottom: Parabolic

Performance of a 20 m diameter Cherenkov imaging telescope
A. Akhperjanian & V. Sahakian
Schwarzschild-Couder two-mirror IACT telescope

RMS spread in arrival time of rays at focal plane as a function of field angle.
Design is isochronous on optical axis.

V.Vassiliev, S.Fegan, P.Brousseau:
Wide field aplanatic two-mirror telescopes for ground-based γ-ray astronomy
Astropart.Phys. 28, 10 (2007)
The mirror and the focal plane have their centre of curvature at the centre of the corrector plate.

The Schmidt corrector is shown with the aspheric shape magnified by a factor of 20.

Both the nominal corrector and a Fresnel version is shown.
CTA desiderata

Sharper PSF gives less background

Sky brightness:
(a) Dark sky; $m_V \approx 21.5 \text{ mag} / \text{arcsec}^2$
(b) Full Moon; $m_V \approx 18 \text{ mag} / \text{arcsec}^2$

$\Rightarrow m_V \approx 9.4 \text{ (a) and } 5.9 \text{ (b) for 5 arcmin } \varnothing$
$\Rightarrow m_V \approx 12.9 \text{ (a) and } 9.4 \text{ (b) for 1 arcmin } \varnothing$

CTA desiderata

Detectors & data handling for huge photon fluxes?

Photon counting @ 100 MHz – 10 GHz?
Silicon detector arrays?
PRINCIPLE OF A DIGITAL PHOTON CORRELATOR
DIGITAL PHOTON CORRELATORS @ Lund Observatory 2008/09:
700 MHz clock rate (1.4 ns time resolution)
200 MHz maximum photon count rates per channel (pulse-pair resolution 5 ns)
8 input channels for photon pulses at TTL voltages

Custom-made by Correlator.com for applications in intensity interferometry
Support of the central pixel, and a camera rear-side photograph with the PMT installed

The mechanical support holding the PMT at the central aperture position, consists of two parts:
* One part is fixed to the metal support plate (dubbed “Swiss cheese” because of its many holes)
* The second part, containing the PMT, is screwed into the central aperture of the “Swiss cheese” plate

The Central Pixel of the MAGIC Telescope for Optical Observations
A 7-pixel camera was custom-built and mounted on the lid of the Cherenkov camera of a H.E.S.S. telescope using a plane secondary mirror to put it into focus.

Its central pixel was used to continuously record the light curve of the target, while a ring of six ‘outer’ pixels was used both to monitor the sky background level and as a veto system to reject background events occurring in the atmosphere.
**CTA desiderata**

Telescopes in optimal pattern to cover interferometric \((u,v)\)-plane?  

Important only for larger telescopes, or will the plane be filled in anyway?
“OPTIMAL” TELESCOPE PLACEMENTS FOR INTERFEROMETRY?

Examples of optimization using different criteria:
Top: Noise at the spatial frequency that is most attenuated by the optical system
Bottom: Average noise at all relevant frequencies

L.M. Mugnier, G. Rousset, F. Cassaing
Aperture configuration optimality criterion for phased arrays of optical telescopes
Tentative CTA recommendations

Desire also smaller telescopes to be isochronous ( < 1 ns)

Desire telescopes with best feasible image quality

Provision to refocus on infinity

Electronic access to standard detectors in central pixel(s)

Provision to mount optics in front of central pixel(s)

Limit photon count rates with wavelength filters

Photon pulse train precise to < 1 ns to computing station

Avoid placing the large telescopes on a regular grid

Avoid placing telescopes on east-west patterns
“Homework” to be done

Prototype instrumentation & test observations
Real-time or off-line correlation?
Understanding detector noise sources
Understanding noise sources in the sky
Software tracking stars across the sky *(LOFAR, MeerKAT?)*
Astrophysical targets and their spectral features?
Simultaneous observations in different wavelengths?
Understanding information content in correlation functions
Demonstrate possible “full” image reconstruction?
A group from the Workshop on Stellar Intensity Interferometry @ StarBase Utah, Grantsville, Jan. 2009
“Our local Universe is teeming with stars, but despite 400 years of telescopic observations, astronomy is still basically incapable of observing stars as such!

Although we can observe the light radiated by them, we do not (with few exceptions) have the capability to observe the stars themselves, i.e., resolving their disks or viewing structures across and outside their surfaces (except for the Sun, of course!).

One can just speculate what new worlds will be revealed once stars no longer will be seen as mere point sources but as extended and irregular objects with magnetic or thermal spots, flattened or distorted by rapid rotation, and with mass ejections monitored in different spectral features as they flow towards their binary companions.

It is not long ago that the satellites of the outer planets passed from being mere point sources to a plethora of different worlds, and one might speculate what meager state extragalactic astronomy would be in, were galaxies observed as point sources only.”

(Dravins & LeBohec, SPIE Proc. 6986, 2008)