INTENSITY INTERFEROMETRY
FROM ASTRONOMY TO PARTICLE PHYSICS, AND BACK

Dainis Dravins — Lund Observatory

www.astro.lu.se/~dainis
**Quest for highest-resolution imaging in astronomy**

- **Galileo Galilei (1609)**
- **Lord Rosse (1845)**
- **Hubble Space Telescope (1990)**
Quest for highest-resolution imaging in astronomy

ELT, Extremely Large Telescope, Cerro Armazones, Chile (~2024)
Quest for highest-resolution imaging in astronomy

LUVOIR
Large Ultraviolet / Optical / Infrared Surveyor

To be evaluated in the U.S. 2020-2030
Astronomy and Astrophysics Decadal Survey
European VLBI radio network
http://www.evlbi.org/

Quest for highest-resolution imaging in astronomy
PROBING THE INNERMOST REGIONS OF AGN JETS AND THEIR MAGNETIC FIELDS WITH \textit{RadioAstron}. I. IMAGING BL LACERTAE AT 21 \( \mu \)as RESOLUTION

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RadioAstron polarimetric space VLBI images of BL Lac at 22 GHz (\( \lambda \) 13.6 mm)

Space–ground fringe detections were obtained up to a projected baseline length of 7.9 Earth diameters.
Highest-resolution imaging in the optical?
ANGULAR SCALES IN ASTRONOMY

- Sun, Moon ~30 arcmin
- Planets ~30 arcsec
- Largest stars ~30 mas
- Typical bright stars ~1 mas
History of optical interferometry

(Commissaires : MM. Le Verrier, Fizeau, Janssen.)

« Dans une Communication précédente (Comptes rendus, t. LXXVI, p. 1008), j’ai eu l’honneur de rappeler à l’Académie une idée anciennement émise par M. Fizeau sous forme de simple aperçu et qui, jusque-là, semblait être restée dans l’oubli, bien que renfermant le germe de conséquences fort importantes. Cette idée peut se formuler comme il suit : Dans plusieurs cas, en donnant naissance à certains phénomènes d’interférence, on peut augmenter la sensibilité des instruments d’optique ordinaires.

» Guidé par l’illustre physicien, j’ai cherché à déduire de cette conception originale quelques notions précises sur le diamètre apparent des étoiles fixes, et, dans la Note citée plus haut, j’ai fait connaître à l’Académie le résultat de quelques expériences préliminaires dont il convient de rappeler le principe général.
Edouard Stéphan (1837-1923)

80-cm telescope at Observatoire de Marseille
La Nature 1, 371 (1873)
"L'instrument dont j'ai fait usage à Marseille est le grand télescope Foucault, de 80 centimètres de diamètre, muni d'un écran lunulaire; les lunules sont limitées par des cercles égaux de 80 centimètres; leurs grands axes sont parallèles et distants de 65 centimètres.

En d'autres termes, les expériences citées ne prouvent pas seulement que le diamètre apparent des étoiles examinées est inférieur à 0''158, elles montrent encore que ce diamètre est une très-faible fraction du nombre précédent. »

E.Stéphan:
_Sur l'extrême petitesse du diamètre apparent des étoiles fixes_
Mt. Wilson, CA, site of the 100-inch Hooker telescope
FIRST SUCCESSFUL STELLAR INTERFEROMETER

20-ft Michelson Stellar Interferometer c. 1919
Unsuccessful attempt at longer-baseline interferometry on Mt. Wilson
FIRST SUCCESSFUL OPTICAL INTERFEROMETER OF THE MODERN ERA (1974)
I2T, *Interféromètre à 2 Télescopes* (Observatoire de CERGA, France)
Principles of interferometry

Interference of light
Synthetic Aperture Imaging with an Interferometer

A. Quirrenbach: Introduction to Interferometry; ESO Santiago
Aperture synthesis & interferometric imaging
Aperture synthesis began in the radio

THE SYNTHESIS OF LARGE RADIO TELESCOPE S

M. Ryle and A. Hewish

(Received 1959 August 24)

Summary

Many investigations in radio astronomy are limited by the resolving power which can be achieved by conventional methods of aerial construction.

A new method of obtaining increased resolving power has been developed, which has been applied to the construction of both "pencil-beam" systems and interferometers. In this method two aerials are arranged so that their relative position may be altered to occupy successively the whole area of a much larger equivalent aerial. By combining mathematically the information derived from these different positions, it is possible to obtain a resolving power equal to that of the large equivalent aerial. Since the combination of the individual records may be done with different phase relationships, it is possible, without extra observations, to "scan" the synthesized aerial over an appreciable solid angle; because of this the total observing time of a synthesized instrument is of the same order as that of a conventional instrument.

An interferometric system designed for the study of radio stars has been built which has an equivalent area for resolution of $8 \times 10^4$ sq. ft as well as a "pencil-beam" system with an equivalent area of $3 \times 10^8$ sq. ft. The sensitivity of both systems corresponds to a "collecting area" of about $2 \times 10^8$ sq. ft.

Sir Martin Ryle (1918-1984)

Nobel prize in physics 1974

"for pioneering research in radio astrophysics: for observations and inventions, in particular of the aperture synthesis technique"

The long fixed element of the radio star interferometer.
VLA: The Karl G. Jansky Very Large Array, a radio interferometer located on the Plains of San Agustin, west of Socorro, New Mexico, http://www.vla.nrao.edu/
UV plane sampling using the earth rotation

North-South & East-West baseline as seen from a star at $\delta=-42\text{deg.}$
ESO VLTI

Very Large Telescope Interferometer
ESO, Cerro Paranal, Chile
VLTI, Very Large Telescope Interferometer
VLI auxiliary telescopes at ESO Paranal
VLTI stations for auxiliary telescopes, above the ducts that lead to the interferometric tunnel.
VLTI delay-line tunnel
AMBER (Astrometrical Multi BEam combineR) – VLTI three-way beam combiner.
Combines light of three telescopes, and disperses it to analyze its spectrum. The complex optical table is required to clean up and adjust the beams from the three telescopes.
VLTI Fringes of Sirius
Interferometric science
Actual image of the Mira-type variable T Leporis from VLTI

Image obtained by combining hundreds of interferometric measurements

Central disc shows stellar surface, surrounded by a spherical shell of expelled molecular material

Infrared wavelengths color-coded:
Blue = 1.4 – 1.6 µm
Green = 1.6 – 1.75 µm
Red = 1.75 – 1.9 µm

In the green channel, the molecular envelope is thinner

The size of Earth’s orbit is marked.

Resolution = 4 milli-arcseconds

(ESO press release 0906, Feb. 2009)
SHAPE OF ACHERNAR

Image of the rapidly rotating (\(V \sin i \approx 250 \text{ km/s}\)) star Achernar (\(\alpha\) Eri, B3 Vpe), from VLTI VINCI observations.

Axis ratio = 1.56, the most flattened star seen until then.

Because of the projection effect this ratio is a minimal value; the star could be even flatter.

Individual diameter measurements are shown by points with error bars.

Vega (α Lyrae)

- Vega is a rapidly rotating star, seen pole-on.
- Axis inclination strongly affects values for abundances, mass, age.
- Problem, since Vega is (was?) the spectrophotometric standard.
Diameters of the giant star β Pegasi

A.Quirrenbach: Introduction to Interferometry; ESO Santiago
Pulsation curves for two Cepheid variables, η Aql and ζ Gem, revealing changes of stellar diameters. Data from the PTI interferometer at 1.65μm; when combined with radial velocities, accurate distances to these primary distance indicators are obtained (Lane et al., ApJ 573, 330, 2002).

Interferometric images of the F-type giant ε Aurigae during its month-long eclipse by an opaque disk, occurring every 27 years

B.Kloppenborg; R.Stencel; J.D.Monnier; G.Schaefer; M.Zhao; F.Baron; H.McAlister; T. ten Brummelaar; X.Che; et al.: Infrared images of the transiting disk in the ε Aurigae system, Nature 464, 870 (2010)
NPOI
Navy Precision Optical Interferometer
Flagstaff, Arizona
NPOI, Navy Precision Optical Interferometer, Arizona

Photo: Dainis Dravins
NPOI, Navy Precision Optical Interferometer

Photo: Dainis Dravins
NPOI, Navy Precision Optical Interferometer, Arizona

Photo: Dainis Dravins
NPOI, Navy Precision Optical Interferometer, Arizona

Photo: Dainis Dravins
NPOI, Navy Precision Optical Interferometer, Arizona

Photo: Dainis Dravins
GEOs at Imaging

- 2009: 1st Interferometric detection of GEOs at during “glint”

Hindsley et al. 2011, Applied Optics, 50, 2692

**IMAGING GEOSTATIONARY SATELLITES?**
Many stars become resolved surface objects for baselines 100-1000 m.

Kilometer-scale interferometry!?
Concordia Base @ Dome C (3233 m)

http://www.esa.int/Our_Activities/Human_Spaceflight/Concordia
http://blogs.esa.int/concordia/
Imaging synthesis optical array proposed at Concordia Base on Dome C in Antarctica. KEOPS individual telescopes are grouped around the optical recombiner. Concordia station is visible in the distance.

Stellar Imager (SI)

K.G.Carpenter, C.J.Schrijver, M.Karovska & SI Mission Concept Development Team;
http://hires.gsfc.nasa.gov/si/
ARAGOSCOPE
Webster Cash, University of Colorado
NASA Innovative Advanced Concept (NIAC) study (2015)
The *Luciola* flotilla of many small collector mirrors operates like one giant diluted mirror. Focal beam-combiners independently exploit the sky image formed at the focal surface.

Exo-Earth Imager (150 km baseline space interferometer) with a simulated 30-min exposure of Earth at 3 parsec distance. (Antoine Labeyrie, Obs. de Haute-Provence)
Isn’t there some easier way??
Air Cherenkov Telescopes
Air Cherenkov Telescopes

[Diagram showing air showers and Cherenkov light]
AIR CHERENKOV TELESCOPES
High Energy Stereoscopic System (H.E.S.S.) array of Imaging Atmospheric Cherenkov Telescopes (IACT) Telescopes, Khomas Highland, near Windhoek, Namibia
Four 23-m and fifteen 12-m telescopes will supplement two existing MAGIC 17-m dishes


Webcam from LST-1 construction site:
http://www.lst1.iac.es/webcams/current1/1000.jpg
Artist’s vision of CTA-South in Chile

Artist’s vision of CTA-South, with different small-, medium-, and large-size telescopes

Paranal-Armazones area: Access road to Armazones (green), electricity grid connections, and location of CTA South.
(T.de Zeeuw: Reaching New Heights in Astronomy — ESO Long Term Perspectives, ESO Messenger 166, 2, 2016)
Future site of CTA-south, ~10 km south-east from the ESO Paranal observatory

(ESO Announcement ann15058)
Intensity interferometry
Intensity interferometry ... the early days

Narrabri observatory with its circular railway track

Intensity interferometry ... the early days

Flux collectors at Narrabri

(University of Sydney)
Intensity interferometry ... the early days

Left: Narrabri electronics of the 1960’s

Top right: Sirius observed from Narrabri
(Hanbury Brown et al., MNRAS 167, 475, 1974)

Bottom right: Simulated Narrabri observations using current software
(Travins et al., New Astron. Rev. 56, 143, 2012)
$P_1 = \alpha_1 \langle I_1 \rangle \Delta t$

$P_2 = \alpha_2 \langle I_2 \rangle \Delta t$

$P_{12} = \alpha_1 \alpha_2 \langle I_1 \rangle \langle I_2 \rangle (1 + |\gamma_{12}|^2) \Delta t^2$

D. Dravins, S. LeBohec, H. Jensen, P. D. Nuñez:  
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**

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**PHOTON ARRIVAL TIME**

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”
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.

50 years hence...

Google Earth;
Site visit by Peter Lawson, 2003
50 years hence…

Sic transit gloria mundi…

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

Photos: Dainis Dravins
Astronomy out ... particle physics in
Influence of Bose-Einstein Statistics on the Antiproton-Proton Annihilation Process*

Gerson Goldhaber, Sulamith Goldhaber, Wonyong Lee, and Abraham Pais†

Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California
(Received May 16, 1960)

Recent observations of angular distributions of $\pi$ mesons in $\bar{p}-p$ annihilation indicate a deviation from the predictions of the usual Fermi statistical model. In order to shed light on these phenomena, a modification of the statistical model is studied. We retain the assumption that the transition rate into a given final state is proportional to the probability of finding $N$ free $\pi$ mesons in the reaction volume, but express this probability in terms of wave functions symmetrized with respect to particles of like charge. The justification of this assumption is discussed. The model reproduces the experimental results qualitatively, provided the radius of the interaction volume is between one-half and three-fourths of the pion Compton wavelength; the dependence of angular correlation effects on the value of the radius is rather sensitive. Quantitatively, there seems to remain some discrepancy, but we cannot say whether this is due to experimental uncertainties or to some other dynamic effects. In the absence of information on $\pi-\pi$ interactions and of a fully satisfactory explanation of the mean pion multiplicity for annihilation, we wish to emphasize the preliminary nature of our results. We consider them, however, as an indication that the symmetrization effects discussed here may well play a major role in the analysis of angular distributions. It is pointed out that in this respect the energy dependence of the angular correlations may provide valuable clues for the validity of our model.
1.2 GGLP

In 1959, Goldhaber, Goldhaber, Lee and Pais performed an experiment at the Bevalac/LBL, in Berkeley, CA, USA, aiming at the discovery of the $\rho^0$ resonance[4]. In the experiment, they considered $\bar{p}p$ collisions, at 1.05 GeV/c. They were searching for the resonance by means of the decay $\rho^0 \rightarrow \pi^+\pi^-$, by measuring the unlike pair, $\pi^+\pi^-$, mass-distribution and comparing it with the ones for like pairs, $\pi^\pm\pi^\pm$. Afterwards, they concluded that there was not enough statistics for establishing the existence of $\rho^0$. Nevertheless, they observed an unexpected angular correlation among identical pions! Later, in 1960, they successfully reproduced the empirical angular distribution by a detailed multi-$\pi$ phase-space calculation using symmetrized wave functions for LIKE particles. Being so, they concluded the effect was a consequence of the Bose-Einstein nature of $\pi^+\pi^+$ and $\pi^-\pi^-$. They were not aware of the experiment Hanbury-Brown and Twiss had performed previously. Thus, they had discovered, by chance, the counterpart of the HBT effect in high energy collisions.
1.5 Further applications

In the 1970’s, Kopylov, Podgoretskiï, and Grishin[8] used second-order interferometry to study several interesting problems. For example, they modelled the nucleus as a static sphere with radius \( R \), emitting pions from its surface and got the following correlation function

\[
C(k_1, k_2) = 1 \pm \left[ \frac{2J_1(q_T R)}{q_T R} \right]^2 \left[ 1 + (q_0 \tau)^2 \right]^{-1},
\]  

(13)

2.1 Expansion effects in HBT

In the first paper on the subject, we started by making the hypothesis that the Quark-Gluon Plasma was already being produced in \( pp \) and \( \bar{p}p \) collisions at the CERN/ISR. We considered[25] that the system produced in such collisions expanded before emitting the final particles (hadrons), according to the one-dimensional Landau Hydrodynamical Model [26]. In the initial stage, the system was formed in the QGP phase at a certain temperature, \( T_0 \), started expanding and cooling down, until it reached the critical temperature, \( T_c \), which we assumed to be of order of pion mass. It could be imagined that, once \( T_c \) was reached, the hadronization occurred instantaneously, followed by the particle emission.
HBT Interferometry: Historical Perspective

Sandra S. Padula
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Received on 13 December, 2004

I review the history of HBT interferometry, since its discovery in the mid 1990’s, up to the recent developments and results from BNL/PHIC experiments. I focus the discussion on the contributions to the subject given by members of our Brazilian group.

Figure 13. $\pi^- \pi^-$ correlations in central Si+Au collisions is shown as a function of $q_T$ and $q_L$. The preliminary E802 data[43] corrected for acceptance and Coulomb effects are shown in part (a). Parts (b) and (c) show theoretical correlation functions filtered with the E802 acceptance. They correspond, respectively, to cases without and with resonance production.

Figure 4. Simple illustration corresponding to the ideal Gaussian source. The upper curve represents the bosonic case, while the lower curve, the fermionic one. The parameter $R$ is the r.m.s. radius of the emitting region.
BOSONS BUNCH TOGETHER, FERMIONS DON’T

Pauli exclusion principle: Fermions cannot share the same quantum state

(but bosons can! 😊)

Bose-Einstein condensates of lithium isotopes;

Left: $^7$Li bosons (integer spin)

Right: $^6$Li fermions

As temperature drops, bosons bunch together, while fermions keep their distance

Truscott & Hulet (Rice Univ.)
HBT Interferometry: Historical Perspective
Sandra S. Padula
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Received on 15 December, 2004

Review of HBT or Bose-Einstein correlations in high energy heavy ion collisions
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Abstract. A brief review is given on the discovery and the first five decades of the Hanbury Brown-Twiss effect and its generalized applications in high energy nuclear and particle physics, including recent developments. Interesting and inspiring new directions are also highlighted, including for example source imaging, leptons and photon interferometry, meta-Gaussian shape analysis as well as many other new directions. Existing models are compared to two-particle correlation measurements and the so-called RHIC HBT puzzle is resolved. Evidence for a (directional) bubble flow is presented and the conclusion is confirmed by a successful description of the pseudorapidity dependence of the elliptic flow as measured by Au+Au collisions by the PHOBOS Collaboration.

HADRONIC INTERFEROMETRY IN HEAVY-ION COLLISIONS
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KEY WORDS: intensity interferometry, Hanbury Brown and Twiss effect, two-particle correlation functions, transport theory

THE PHYSICS OF HANBURY BROWN-TWISS INTENSITY INTERFEROMETRY: FROM STARS TO NUCLEAR COLLISIONS
Gordon Baym
Department of Physics, University of Illinois at Urbana-Champaign
1100 W. Green St., Urbana, IL 61801, USA

Received April 14, 1998

In the 1960's Hanbury Brown and Twiss showed that one could measure the angular size of astronomical radio sources and stars from correlations of their radiation. Their use of phasematching has been providing new insight into the basis of high energy nuclear and particle physics. The views presented here rely on a combination of results of each of the interferometric measurements. A physical description is given of the possible origin of the observation.

Two-Particle Correlations in Relativistic Heavy-Ion Collisions
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Key Words. Hanbury Brown-Twiss interferometry, Bose-Einstein correlations, collective expansion, source size/lifetimes

Abstract. Two-particle momentum correlations between pairs of identical particles produced in relativistic heavy ion collisions are expected to depend on the shape of the nuclei and the flow pattern of the reaction products. The results of several experiments and theoretical calculations for Au+Au collisions at 39 GeV are presented.

FEMTOSCOPY IN RELATIVISTIC HEAVY ION COLLISIONS: Two Decades of Progress
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Key Words. HBT, intensity interferometry, heavy ion collisions, femtoscopic

Abstract. Analysis of two-particle correlations have provided the chief means for determining spatio-temporal characteristics of relativistic heavy ion collisions. We discuss the theoretical formalism behind these studies and the experimental methods used in carrying them out. Recent results from RHIC prelude in context a systematic review of correlation measurements performed over the past two decades. The current understanding of these results is discussed in terms of model comparisons and overall trends.
Back to astronomy ...
Intensity interferometry

**Pro:** Time resolution of 10 ns, say, implies 3 m light travel time; no need for more accurate optics nor atmosphere.

Permitted error budget is ~meter, not ~wavelength of light!

**Virtually immune to atmospheric turbulence!!**

**Con:** Require high photometric precision, large flux collectors.

Method not pursued in astronomy since numerous large and widely spread telescopes have not been available.
Proposed configurations of the Cherenkov Telescope Array

Image: G. Pérez, IAC

CTA - North

LST 24 m

MST 12 m

SST 6 m

1 km²

CTA - South

3 km²
Software telescopes in radio and the optical

Low-frequency radio waves, \(~100\) MHz

Many antennas, huge data flows.
Radio-wave amplitude sampled 12 bits deep.
Spectral resolution \(~1\) kHz, bandwidth 32 MHz.
Measures first-order coherence.
Large, central on-line data processing facility.

Optical Intensity Interferometer

Low-frequency optical fluctuations, \(~100\) MHz

Many telescopes, moderate data flows.
Photon counts recorded (1 bit).
Spectral resolution by optical filters.
Measures second-order coherence.
On-line or off-line data processing.
Laboratory & field experiments

Verify operation of an intensity interferometer; understand detector properties, issues in data handling
VERITAS telescopes at Basecamp, Arizona
Site of first full-scale tests of digital intensity interferometry

* Digitally correlated pairs of 12-m telescopes
* Photon rates >30 MHz per telescope
* Real-time cross correlation, $\Delta t = 1.6 \text{ ns}$

(D.Dravins & S.LeBohec, Proc. SPIE 6986)
The StarBase 3 m Cherenkov telescopes are protected by buildings which can be rolled open for observation. The control room is located between the two telescopes.

D.Dravins, S.LeBohec, H.Jensen, P.D.Nuñez:
Left: One of the StarBase telescopes, having 19 hexagonal mirror facets with total diameter of 3 m.
Right: Light is detected by the intensity interferometry camera consisting of a single PMT ‘pixel’

N. Matthews, O. Clarke, S. Snow, S. LeBohec, D. Kieda
*Implementation of an intensity interferometry system on the StarBase observatory*
Observing interface at StarBase during stellar observations

N. Matthews, O. Clarke, S. Snow, S. LeBohec, D. Kieda
Implementation of an intensity interferometry system on the StarBase observatory
VERITAS Cherenkov telescope on Mt. Hopkins, Arizona

Camera baseplate for interferometry
(David Kieda, Univ. of Utah, Sept. 2018)
Initial Target Source – Bellatrix

- Simulations of a 6-hr observation of Bellatrix (gamma Orionis) about the meridian using T3-T4 telescopes.

- Solid line is model curve based on known angular diameter

- Dashed lines show curve +/- 10% of expected diameter (quick literature search shows something like 7% precision in current measurement)

- Uncertainties estimated by scaling from StarBase count rate by mirror areas
  → Does not include systematics
  → Possible to observe earlier/later for shorter baseline coverage

David Kieda & Nolan Matthews  (University of Utah, 2018)
The ongoing VERITAS upgrade includes provisions also for intensity interferometry. Here, David Kieda examines correlation functions computed off-line in electronics for real-time digitization and storage of photomultiplier signals.
Intensity fluctuations in polarized light

Temporal coherence from a Hg arc lamp in the laboratory. Upper plot: Non-correlation with perpendicular polarizations. Lower: Observed 2-photon correlation with parallel polarizer configuration.

D. Kieda, N. Matthews

Stellar intensity interferometric capabilities of IACT arrays

ASTRI* small-size telescope array

To be set up the CTA Southern site

Telescope spacing ~250 m (drawing here not to scale), well suitable for intensity interferometry

*Astrofisica con Specchi a Tecnologia Replicante Italiana
Luca Zampieri, Gabriele Rodeghiero, Giampiero Naletto, for the ASTRI collaboration
ASTRI prototype Cherenkov telescope, Serra La Nave, Sicily

Photo: Dainis Dravins
Schwarzschild-Couder air Cherenkov telescope

ASTRI project; inaugurated at Serra La Nave observatory on Sicily, 2014

First Schwarzschild-Couder telescope completed since its invention in 1905!
Very fast wide-field optics, f/0.5. Telescope diameter 4.3 m.
Basic concept proposed by Karl Schwarzschild in 1905; developed by André Couder. Challenging optical polishing and alignment requirements; design overtaken by Schmidt telescopes.
ASTRI prototype Cherenkov telescope, Serra La Nave, Sicily

Observations of *Polaris* (Oct. 2016) demonstrate constant PSF over a wide 10-deg field
(E.Giro, R.Canestrari, S.Scuderi, G.Sironi, INAF Padova, Brera & Catania; [www.cta-observatory.org](http://www.cta-observatory.org))
Plateau de Calern, Observatoire de la Côte d’Azur

C2PU telescopes, altitude = 1280 m
Twin 1-m telescopes – *Omicron & Epsilon*, Plateau de Calern, Observatoire de la Côte d’Azur

Photos: Serge Brunier (top), Hervé de Brus (right)
Setup at telescopes on Plateau de Calern

I2C Consortium –
Intensity Interferometry at Calern

Institut de Physique de Nice (INPHYNI), Université Côte d’Azur & CNRS
Starlight is collected by two 1-m telescopes and fed into multimode optical fibers (MMF) to an avalanche photodiode (APD), followed by a time-to-digital converter (TDC).

*Spatial intensity interferometry on three bright stars*
Photon bunching (intensity correlations) measured on one 1-m telescope

Temporal intensity correlation measured for three different stars. Gaussian fits are dashed.

(a) α Boo (Arcturus).
(b) α CMi (Procyon).
(c) β Gem (Pollux).

Temporal intensity interferometry: photon bunching in three bright stars
Laboratory simulations

End-to-end operation of intensity interferometry in the laboratory: artificial stars; telescope array; photon-counting detectors; reconstructed images.
Diffraction patterns with laser light show the [squared] Fourier transforms of some artificial ‘stars’. Circular single star; elliptic small single star; binary with equal components. Image widths correspond to ~70 cm in the telescope plane and such baselines are required to retrieve these patterns.

How to make an artificial star?

S/N in intensity interferometry depends not only on instrumentation but also on the source brightness temperature.
Light from a 300 mW $\lambda$ 532 nm laser is randomized through scattering against microscopic particles in a square-top cuvette and focused by a condenser onto artificial ‘stars’, being apertures in a rotatable holder. The ‘stars’ are observed by an array of small telescopes, each with a photon-counting SPAD detector. 2-D coverage is achieved by rotating the asymmetric source relative to the plane of the telescopes.

Intensity Interferometry correlator
Multi-channel, real-time, FPGA
32 channels \(\sim 20 \text{ k€}\)

ALMA correlator
134 million processors

Very much more modest computations than in radio interferometry!
Second-order coherence $g(2)$ measured for artificial single stars of different angular sizes. Superposed are Airy functions for circular apertures (squared moduli of the Fourier transforms).

One-dimensional coherence functions sample one particular position angle of the two-dimensional coherence surface, here a sequence of measured points on the surface for an idealized circular aperture.

Laboratory intensity interferometry with many baselines

Second-order coherence $g(2)$ for an artificial binary star with each component of diameter $\sim 1$ arcsec. This coherence surface was produced from intensity correlations measured across 60 different non-redundant baselines, illustrating how a telescope array fills in the interferometric plane. The central maxima (left) indicate the binary separation while the symmetric rings reveal the size of individual stars.

Intensity interferometry measurements with 100 different telescopic baselines. The data largely fill the interferometric \((u,v)\)-plane of the second-order coherence \(g(2)\) for an artificial star, somewhat irregular and elliptic, with angular extent just below 1 arcsecond. At right, the projection of the 3-D mesh is oriented straight down, showing [the modulus of] the source’s Fourier transform (‘diffraction pattern’).

Laboratory intensity interferometry with 180 baselines

Measured second-order spatial coherence $g^{(2)}$ from intensity interferometry over 180 telescopic baselines. The source is an artificial binary star with differently large components. The structure corresponds to the pattern that would be produced by coherent light undergoing diffraction in a corresponding aperture.

Image reconstruction

Second-order coherence $g^{(2)}$

$$g^{(2)}(\tau) = 1 + \left| g^{(1)}(\tau) \right|^2$$

Does not retain phase information, 
*direct* image reconstruction not possible.

Imaging requires retrieval of Fourier phases from amplitudes.

Feasible if dense coverage of (u,v)-plane
Two-dimensional images can be reconstructed without phase information, provided two-dimensional coverage of the \((u,v)\)-plane is available.

This Airy-disk diffraction pattern is immediately recognized as originating in a circular aperture, although only intensities are recorded.
Numerical simulations of intensity-interferometry observations with a CTA-like array, with image reconstruction of a star with three hotspots

Pristine image has $T = 6000$ K; spots have 6500K (top-right and left) and 6800K.

Simulated data correspond to visual magnitude $m_v = 3$, and 10 hours of observation.

Optical images reconstructed from intensity interferometry. Measurements with 100 and 180 baselines, of an elliptical ‘star’, and a binary with brightness ratio 1:4.

First diffraction-limited images from an array of optical telescopes with no optical connections between them... AS FAR AS WE ARE AWARE ...
Cramér-Rao lower bound and object reconstruction performance evaluation for intensity interferometry

Jean J. Dolne\textsuperscript{a}, David R. Gerwe\textsuperscript{b}, and Peter N. Crabtree\textsuperscript{c}

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Image reconstruction of a geostationary satellite using a nominal CTA layout, and scaled versions

Image Reconstruction from Sparse Irregular Intensity Interferometry Measurements of Fourier Magnitude

David R. Gerwe, J. J. Dolne  
*Boeing Phantomworks Space & Intelligence Systems*

Peter N. Crabtree  
*United States Air Force Research Labs*

Richard B. Holmes, Brandoch Calef  
*Boeing Laser and Technical Services*
S/N in intensity interferometry

PROPORTIONAL TO:
★ Telescope areas (geometric mean)
★ Detector quantum efficiency
★ Square root of integration time
★ Square root of electronic bandwidth
★ Photon flux per optical frequency bandwidth

INDEPENDENT OF:
★ Width of optical passband
Simulated observations in intensity interferometry

Squared visibility from a close binary star.
Left: Pristine image; Right: Logarithm of magnitude of Fourier transform

D.Dravins, S.LeBohec, H.Jensen, P.D.Nuñez:
Simulated observations in intensity interferometry

Limiting magnitude for CTA with foreseen instrumentation

$m_v = 3$  $m_v = 5$  $m_v = 7$

Simulated observations of binary stars of visual magnitudes 3, 5, and 7.
Total integration time: 20 hours; $\lambda$ 500 nm, time resolution 1 ns, quantum efficiency = 70%
Array: CTA D

D. Dravins, S. LeBohec, H. Jensen, P. D. Nuñez:
Limits to time resolution?
Isochronous telescopes?

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.
Top: Spherical (Davies–Cotton)

A spherical reflector substantially widens the photon pulse.

At detecting 10 GeV γ-shower, 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 $\gamma$-ray astronomy
Astropart.Phys. 28, 10 (2007)
Multiple spectral channels?
For clarity of display the number of channels and their widths has been adjusted from actual values.

84 Channels

Wavenumber µm⁻¹

25 Contiguous Sub-Channels

2.353 2.354 2.355 2.356 2.357 2.358 2.359 2.36

S/N improves by measurements in multiple spectral intervals

Image Reconstruction from Sparse Irregular Intensity Interferometry Measurements of Fourier Magnitude

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Boeing Laser and Technical Services

AMOS, Advanced Maui Optical and Space Surveillance Technologies Conference, Technical Papers; 2013
Multiple spectral channels?

Left: Output from a multimode fiber onto a prism to disperse the light
Right: Possible layout to operate between multi- and single-mode fibers

*Intensity interferometry revival on the Côte d’Azur*
Imaging dark objects with intensity interferometry

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Abstract: We have developed a technique for imaging dark, i.e. non-radiating, objects by intensity interferometry measurements using a thermal light source in the background. This technique is based on encoding the dark object’s profile into the spatial coherence of such light. We demonstrate the image recovery using an adaptive error-minimizing Gerchberg-Saxton algorithm in case of a completely opaque object, and outline the steps for imaging purely refractive objects.

Results of simple image recovery algorithm

Gaussian source with rectangle, reconstructed by Gerchberg-Saxton algorithm
CTA Potential

An optical equivalent to VLBI!

(Michael Daniel, CfA Center for Astrophysics & VERITAS, Fred Lawrence Whipple Observatory)
**Cherenkov Telescope Array as an Intensity Interferometer**

*Expected resolution for assumed exoplanet transit across the disk of Sirius*

Stellar diameter = 1.7 solar
distance = 2.6 pc
Angular diameter = 6 mas

Assumed Jupiter-size planet with rings;
four Earth-size moons;
equatorial diameter = 350 µas.

CTA array spanning 2 km;
Resolution 50 µas at \( \lambda \) 400 nm provides more than 100 pixels across the stellar diameter

Cherenkov Telescope Array as an Intensity Interferometer

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JUPITER’S MOONS

Io

Europa

Ganymede

The First Three Large Satellites of Jupiter in Transit

Upper—Satellite I, Antoniadi’s observations, completed by details discovered by Barnard.

Middle—Satellite II, as seen by Antoniadi Sept. 28, 1927.

Lower—Satellite III, as seen by Antoniadi, with whitish southern spot seen by Barnard.

FIRST DIFFRACTION-LIMITED SQUARE-KILOMETER OPTICAL TELESCOPE

“A thousand times sharper than Hubble”

Intensity interferometry with 1000+ baselines!
THE END