New tools for intensity interferometry

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First experiment in intensity interferometry

- Hanbury-Brown & Twiss 1954
- Correlate detectors’ currents
- 2\textsuperscript{nd} order correlation
- Measures only |γ_{12}|
- Optical accuracy c/Δf \sim 30 \text{ cm}
- Insensitive to atmosphere, optics

Jodrell Bank 1958
Narrabri 1969-74

Fig. 7. The general layout of the interferometer at Narrabri Observatory.
What has changed in the world since 1974?

Amplitude interferometry, for one (and a big one, at that)
But also
• Telescopes: bigger, phased panels, adaptive optics
• Electronics: the transform from analogue to digital
• Optics: modulators, fibres, materials
• Detectors
• Computers
• Data analysis: phase retrieval, speckle methods
All of these were used by amplitude interferometry
Can we gain from them in intensity interferometry?
Which are unique to intensity interferometry?
Advances in technology

Light collectors are better, cheaper
Photomultipliers out, avalanche photodiode arrays in
  ... but analogue technology still has wider band width
Correlators up to $10^9$ bits/s in the radio, Čerenkov
  ... but analogue technology still has wider band width
New other tools
  • Non-imaging light concentrators
  • Long-haul fibre optics (single- and multimode)
  • Other optical paraphernalia: spectrometers, correlators
  • Global positioning systems
  • Correlators on computer clusters (digital again)
Advances in performance: technology

Conservative Technological Effect On SNR vs. N of 30m² Apertures In One Hour of 0 magnitude star

$b_\nu = \text{electronic bandwidth}$
$
\alpha = \text{quantum efficiency}$
$
\Sigma = \text{system efficiency}$
$m = \text{optical channels}$

$b_\nu \rightarrow 1\text{GHz}, \alpha \rightarrow 0.8, \Sigma \rightarrow 0.8, m=1$

NSII performance: 0m star, 1 hr, SNR=27
$b_\nu = 100\text{MHz}, \alpha = 0.2, \Sigma = 0.2, m = 1$

New Tools for Intensity Interferometry
Workshop on Stellar Intensity interferometry
Erez Ribak
Salt Lake City 2009
Advances in theory

- More correlations (Fontana 1983)
  - Higher order correlations
  - Parallel spectral detectors
  - Correlators on computer clusters
- Triple correlation
  - Adds phase information
  - Proposed by Gamo (1963)
  - Demonstrated in lab (Sato 1978)
  - Applied in speckle interferometry (Weigelt, Lohmann 1980s)
- Use zero sheets in the Fourier domain
  - 1-d polynomials (Bates 1984)
  - Cauchy-Riemann equations (Holmes 2008)
Advances in performance: high-order correlations

SNR vs. N of various Apertures \( [m^2] \) in one hour of 0 magnitude star

- Sextuplets: \( N = 71 \)
- Octuplets: \( N = 85 \)
- Nonuplets: \( N = 99 \)
- Septuplets: \( N = 71 \)
- Quadruplets: \( N = 29 \)
- Quintuplets: \( N = 43 \)
- Triples: \( N = 15 \)
- Quadruplets: \( N = 29 \)
- Sextuplets: \( N = 71 \)
- Nonuplets: \( N = 99 \)

Most improvement for sharp-contrast objects (high V)

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Laboratory experiment

- Blue LEDs
- Sheltered light path, light baffles
- Telescopes: Fresnel lenses a few meters away
- Fast photomultipliers at Fresnel foci

LED spectrum

Fresnel collector

Lipson and Spektor (work in progress)
Laboratory communication and correlation

- Fast electronics using current technologies (e.g. optical coupler)
- Employing RF gain/phase detector as phase difference element
  - Analogue function
  - Slight frequency deterioration
  - Up to 2.7 GHz

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*TPC 25. Phase Output (VPHS) vs. Input Phase Difference, Input Levels -30 dBm, Frequencies 100 MHz, 900 MHz, 1900 MHz, 2200 MHz, 2700 MHz, Supply 5 V, 2700 MHz*
Implementation

- Phase difference element
  - Wide frequency range: 0.1→1GHz (local radio stations → PMT limit)
  - Unfortunately device requires frequency to find phase
  - Used only to work at zero phase difference (zero delay)
- First successful results obtained
  - With signal, noise level rises as expected
  - Higher correlation
Formation flight

- Calculation of orbits requiring minimal fuel
- Proper Fourier coverage
- Simple collectors
- UV-blue coverage
- Data handling
  - Transmit photon events
  - Space/ground correlators

Klein, Guellman, Lipson, 2007

Orbits  Fourier coverage
Antarctica

- Medium (~20m) collectors: bigger would resolve objects
- Can be used for coronagraphy (resolve star, not planet)
- Many base lines: simultaneity not so important for closure, but...
- Many ($n>50$) collectors: improvement in SNR $\sim n^{1.1}$ for high $\gamma$
- UV-Vis: complement amplitude interferometry in IR

Presented at 2nd ARENA Workshop on Interferometry, 2008
## Setting up array observatories

<table>
<thead>
<tr>
<th></th>
<th>$\lambda$</th>
<th>surface, delay accuracy</th>
<th>diameter</th>
<th>array area</th>
<th>no. of elements</th>
<th>focal position</th>
<th>signal handling</th>
<th>lunar interference</th>
<th>synergy</th>
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<tbody>
<tr>
<td>Cerenkov detection</td>
<td>µm</td>
<td>µm</td>
<td>m</td>
<td>km</td>
<td></td>
<td>below focus</td>
<td>cross-correlate</td>
<td>high</td>
<td>IceCube</td>
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<tr>
<td>radio interferometry</td>
<td>0.3-1</td>
<td>100</td>
<td>5-25</td>
<td>1×1</td>
<td>10-100</td>
<td>focus, chopper</td>
<td>cross-correlate</td>
<td>low</td>
<td>IceCube</td>
</tr>
<tr>
<td>intensity interferometry</td>
<td>500+</td>
<td>100</td>
<td>5-25</td>
<td>1×1</td>
<td>10-100</td>
<td>focus</td>
<td>cross-correlate</td>
<td>high</td>
<td>-</td>
</tr>
<tr>
<td>amplitude interferometry</td>
<td>0.3-1</td>
<td>0.1</td>
<td>0.5 or 8-10+AO</td>
<td>1×1</td>
<td>5-20</td>
<td>focus, chopper</td>
<td>interfere optically</td>
<td>low</td>
<td>-</td>
</tr>
</tbody>
</table>

- All values are negotiable
- The first three arrays share many parameters
- Some optics can be shared, electronics less so
- Planning and designing a common array is essential for funding

Presented at 2nd ARENA Workshop on Interferometry, 2008
Sharing collectors with Čerenkov detectors

- Focal plane camera is an array of photomultiplier detectors
- Spot size (PSF) is relatively large, for parabolic collectors or Davies-Cotton
- Addition of nearby detector signals encouraged
- Better still: use cross detectors for spectral dispersion
Large telescope interferometers
- Very Large Telescope Interferometer: 4×8m (+ 4×2m)
- Keck Interferometer: 2×10m
- (Narrabri: 2×6.5m)
- Adaptive optics correction
  - Visible source for reference
- Transfer of infra-red beams to combiner, interference
- > 90% of visible light not used
- Can be employed for simultaneous intensity interferometry
  - Employ fastest detectors (10 GHz?)
  - Correlate all with all (6 at VLTI, 2 at KI)
  - Use spectrometer to separate to $m \sim 100$ channels (flux permitting)
  - Parallel correlations for all $m$ channels
- UV coverage better than amplitude interferometry (and higher resolution)
- All measurements are simultaneous (but different $\lambda \rightarrow$ different baselines)
Fibre ring

- New devices convert input light to modulation of laser light
- Evanescent light coupling from IR laser beam in light guide into ring
- Ring resonance depending on size
- Coupling back, transmission drops to zero on main beam

![Image of fibre ring with input and output positions]

- Work by Michal Lipson and group at Cornell EE
All optical modulation

- Now we illuminate the device
- Ring resonance depending on size but also on plasma dispersion
- Free carriers from blue pump beam modify plasma
- Resonance shifts, changes absorbed wave length
- Switching energy $5.35 \times 10^{-15}$ J/bit = $1 \times 10^6$ photons/bit for 10 dB modulation
Optical to optical conversion and correlation

- Send same laser beam to all dishes
- Stellar light to laser *modulation*

If ring too small, **add** many such rings
- Amplify laser beams, if needed (EDFA)
- Divide into parallel channels
- **Correlate** laser signals from other dishes

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System view (vision?)

- Send same laser beam to all dishes
- Stellar light to laser intensity modulation
- If ring too small, add many such rings
- Add baseline delays, as in radio interferometry
- Amplify laser beams, if needed
- Divide into parallel channels
- Correlate laser signals from other dishes

\[ I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \Delta \omega t \]

- All-fibre technology
Astrophysics in one or more bands, synergies

- Studies of jets (galaxies, AGNs, supernovae)
  - Point sources at most wave lengths, fast changes of intensity, spectrum
  - Persistent claims by de Rujula and Dar:
    - Identification of γ-ray bursts with supernovae
    - Successive, relativistic plasma bullets look like jets
    - Spectra and intensity depend strongly on directionality
    - Successful prediction of every afterglow event
- Identification of γ-ray sources (last scatter?)
- Origin of cosmic rays, directionality, GZK limit
- Opposing theories for GRB: clashes between shells of ejecta
- Difficulty: weak signals, unresolvable objects
- Advantage: early GRB warning by satellites
- Interesting for Čerenkov, mm-wave and intensity interferometry
Thank you for your attention

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