Spectral Intensity Interferometry for Quantum Super-resolution

Erez N. Ribak and Georgiy Shoulga
Department of Physics, Technion – Israel Institute of Technology, Technion City, Haifa 32000, Israel
eribak@physics.technion.ac.il

Abstract: Splitting a large light collector into small segments, and dispersing each segment, allows efficient use of stellar light. Higher-order correlations between segments' photon events improve the resolution beyond the diffraction limit.

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1. Introduction

Intensity interferometry, as originally suggested and implemented by Hanbury-Brown and Twiss [1, 2], for measurement of stellar objects, was not efficient enough when compared to amplitude interferometry [3]. However, it turns out that in some cases amplitude interferometry is also limited, and we are interested in such cases. Specifically, when observing in wave lengths shorter than ~0.5 µm, turbulence becomes a severe problem. Similarly, the ultra-violet is only accessible from space, where long base-line interferometry is limited for mechanical reasons. Intensity interferometry is more efficient at shorter wave lengths [2] and is not sensitive to mechanical errors, making the perfect match for these cases. In short, amplitude and intensity interferometry are complementary techniques.

Revival of intensity interferometry was described before [4], on the ground and in space [5-7]. Here we wish to experiment with new notions, and have already started experiments in the laboratory towards this end. Below we describe two such directions: higher-order aberrations for bypassing the diffraction limit, and colour separation for higher efficiency.

2. Single dish or many dishes?

The original HBT interferometer included two 6.5m light collectors, whose outputs intensities were correlated. As one includes more dishes, it becomes possible to have more base lines (Fourier plane sampling points). More dishes also allow using higher order correlations, between three dishes, then between four dishes, etc. These higher correlations have two benefits: they improve the signal to noise ratio [5-8], and at the same time allow getting resolutions which are below the formal diffraction limit [9, 10]: Instead of measuring two entangled photons from the source, it becomes possible to use three (or more) entangled photons. The diffraction limit is due to the Heisenberg uncertainty principle, but with more photons per mode, it allows having better resolution (i.e. momentum) with the same uncertainty in position. This is also the source for enhanced resolution using photon amplification [11, 12]. However, here we rely more on the source producing entangled photons, rather than amplifying astronomical photons.

While setting different light collectors might be complicated (especially when considering space intensity interferometry), it might be easier to use a decameter-size solar or Cherenkov light collector [12]. The surface of this collector is split many ways, each part of the collector roughly focused into a separate focus. This is somewhat similar to using a lenslet array, except that here the required accuracy is rather low, such that even non-imaging optics can be used. The requirements on the flatness of the incoming wave front are not a fraction of the wave length as in amplitude interferometry; rather, the wave front perturbations need to be below the photo-electric response time, corresponding to about 1cm surface deformation. Collectors reach now 30m in diameter, and radio-telescopes are even bigger – these can be used if their surfaces are reflective enough. Possibly, in the future, super telescopes might even be employed [13].

3. Spectral spreading

One of the main advantages of intensity interferometry is that splitting the photons into different spectral bands, and correlating them at their specific colours, can only improve the final signal to noise ratio [2]. Of course, this happens provided that information at all bands is the same so they can be averaged after correlation, and if not, spectral features such as bloated atmospheres at specific spectral lines can be detected. We asked ourselves if it is possible to take an uncollimated beam arriving from a low quality light collector, such as a solar or Cherenkov collector, split it many ways, and spread spectrally the light into a number of channels, of order ten. Each such dispersed spectrum will be collected by an array of fast detectors, photo-multipliers or avalanche photo-diodes. Single photons from each colour will be correlated with simultaneous single photons at the corresponding colours of all parallel segments. The extremely bright background due to correlations of photons of different wave lengths is strongly reduced in this scheme. The main issue here is the beam quality, which is not collimated well enough to produce sharp spectra with multiple channels. We found out that by using dispersing prisms, the tolerance to the input beam quality can be dropped, and the spectrum will be well defined (Fig. 1).

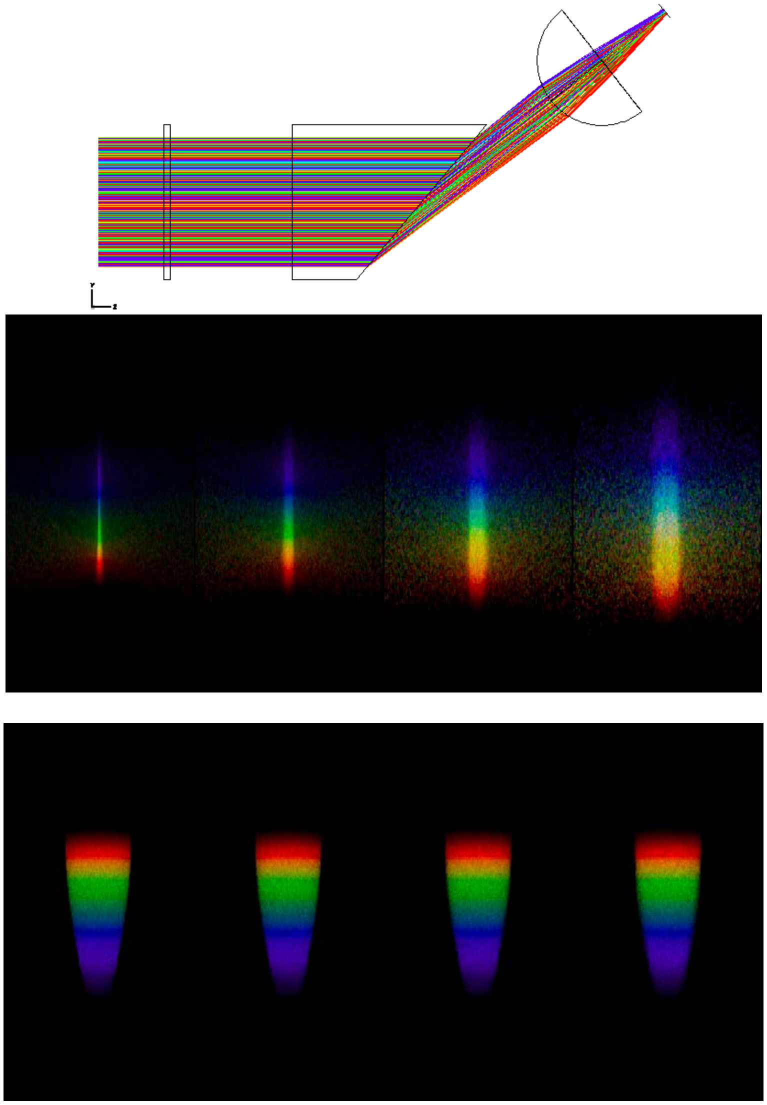

Fig. 1. Initial results for dispersion of one channel facing the collector’s aperture. Light arrives from the left, and is spread and focused on the detector (top right). We show four cases for aberrations of 0^0, 0.1^0, 0.2^0 and 0.3^0. Adding more dispersers improves the spectral resolution (bottom row, same angles).

4. Laboratory experiment

In parallel to simulations, we also tested the option of constructing images of simple objects by using triple correlation resulting from photons from three simultaneous measurements. We set two detectors at a constant distance, and moved a third detector to improve the Fourier place coverage. Indeed, we were able to reconstruct a monochromatic double source quite clearly (Fig. 2). To remove all correlations within the source, we used a fast scatter plate to verify that only one speckle from a laser source was visible to the detectors at the same time.

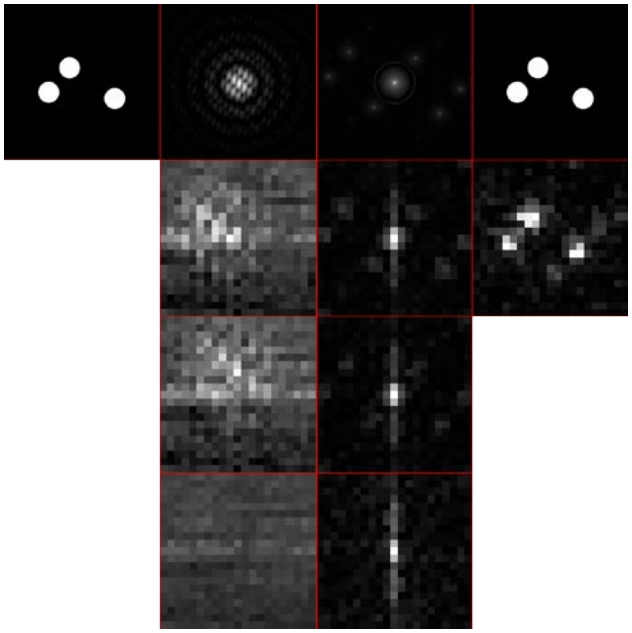

Fig. 2. Simulation and experiment of a three-circle objects (left). The first row represents the simulation. The second row is an experimental result from correlation between PMT 1 and 2. The third row - same between PMT 2 and 3. The fourth row - same between PMT 1 and 3, which are fixed along the entire experiment. The second column displays the Fourier transform of the mask and measured correlation maps (21 by 21 measurements). The third column shows the inverse Fourier transform (both simulation and correlation maps) for intensity only (without phase). The fourth column shows the same with phase.

5. References

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