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SPECTRAL MULTIPLEXING IN INTENSITY INTERFEROMETRY

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Abstract. Intensity Interferometry offers an interesting path forward for astronomical interferometry at very long baselines and at short wavelengths, all leading to extremely high angular resolution. Single photon counting detectors (and associated correlator technology) has evolved to allow a sensitivity gain of two orders of magnitude since the seminal experiments of Hanbury-Brown and Twiss in the 1960s, but sensitivity remains the challenge to make this technique widely useful: extremely high angular resolution requires high surface brightness by definition. The simplest way to increase the sensitivity of an intensity interferometer is to obtain multiple simultaneous correlation measurements at different wavelengths since these are uncorrelated and improve the SNR as $\sqrt{N}$, with N spectral channels. The first issue to address is the break-even point since the throughput of spectrographs can be low; for example a throughput of 50% requires at least 4 spectral channel to break even. The next issue we wish to address is one of reliability and ease of use as we intend to deploy these spectrographs at multiple locations. In this paper, we propose and compare three concepts, each with its advantages and drawbacks: a classical multimode fiber-fed spectrograph, a photonics lantern fed focal plane based concept and an integrated optics solution using photonics lanterns and an Arrayed Waveguide Grating Spectrograph. We hope to build a simple demonstrator of whichever concept we end up choosing for testing in the context of the I2C project.

Keywords: Intensity interferometry, photonics, White Dwarfs, AGN

1 Introduction

Intensity Interferometry (II) allows to reach places that are hard to reach with amplitude interferometry, such as extremely long baseline, short wavelengths or high precision polarisation studies. However, it suffers from a lack of sensitivity compared to amplitude interferometry because the bandpass has to be extremely narrow to detect single photons to be correlated, compared to the coherence length–spectral resolution relationship that amplitude interferometers can make use of for broadband or dispersed measurements. In II, the optical bandwidth has to be large enough to not degrade the timing resolution (it is inversely proportional to the time resolution of the intensity measurements), which is limited by the detector and the Time–to–Digital Converter (TDC, used to obtain the correlation measurements) jitter. TDCs have count rates of several million per second and the best detectors (Single Photon Avalanche Diodes, SPADs or SNSPDs) have a timing measurement jitter of tens to hundred of picoseconds. The electronic bandpass thus has to be smaller than the optical bandpass at optical wavelengths ($\Delta\lambda = \lambda^2/(c\tau_e)$); if the former is on the order of 50∼100 picoseconds, then the latter would be a limiting factor if smaller than 0.1Å . Once this condition is satisfied, it turns out that the SNR is independent of the actual optical bandpass (as long as it doesn't introduce spurious correlations and count rate is much greater than the dark counts (and sky), and is less than the saturation of the detector), because there are more photons to measure the correlation peak, but its absolute value decreased in equal measure.

The original Hanbury-Brown and Twiss experiments (Hanbury Brown et al. 1967) used photocathodes (the correlations were carried out in analog, continuous mode on the current of the photocathodes, and were limited by the electronics), and modern technologies have allowed to gain about two orders of magnitude in timing

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resolution (essentially better detectors such as SPADs and Digital Time correlators). However (and as already noted by Hanbury Brown et al. (1974)), the most efficient way to improve the sensitivity of II is to increase the number of independent spectral channels. While this is true, we note that 100 spectral channels only provides an improvement of 2.5 magnitudes. To be truly transformative and become a complementary to amplitude interferometry, thousands of channels will be needed (e.g. 5000 channels provides a gain of 4.8 magnitudes). Our current brightness range with 1–m class telescopes is around magnitude 3 to 4).

There are however difficulties in the implementation of spectral multiplexing in II. First is the issue of detectors; multipixel SPADs exist (for instance 8×1 linear arrays), but they are not readily available and difficult to interface to SNSPDs show more potential for multipixel arrays, but are not mature enough for hundreds of spectral channels. Another issue is the data storage and post-processing which becomes significant for thousands of spectral channels. Pair-wise real time processing (correlations) may be easier, but doesn't offer the same flexibility in terms of re-using the same data in different ways (e.g. filtering). Finally is the issue of implementation, namely how to disperse the light. We note in passing that it is not spectroscopy *stricto sensu* because although we disperse the light, all the spectral channels must contain the same (spatial and intensity) information to be able to be combined as independent variable. Nonetheless we will use a spectrograph to disperse the light and its throughput will be crucial as there is an effective break-even point below which the gain of multiple spectral channels is canceled by the throughput. If the throughput is 50%, then at least 4 spectral channels are needed to obtain any gain at all and if the throughput is 10%, then more than 100 spectral channels are needed to break even.

2 Astrophysical motivation

2.1 Existing facilities

As with the OHANA project (Perrin et al. 2006), a strong motivation for intensity interferometry is the possibility to retrofit interferometric capabilities to observatories or sites which were not designed with that purpose in mind. The reason why this is especially enticing is because there are many serendipitous hectometric to kilometric baselines between large (8∼10m) and extremely large (>20m) optical telescopes at major observatories. For instance, on Cerro Pachón in Chile, the Gemini South 8m telescope is 420m away from the 4m SOAR telescope and we note in passing that our Brazilian colleagues have access to both. At Las Campanas Observatory, the two 6.5m Magellan telescopes are 60 meters apart and the 24m Giant Magellan Telescope (GMT) will be built 1.7km away.

The summit of Mauna Kea hosts four 8∼10m class telescopes (Gemini North, Subaru and the two Kecks) as well as four 2∼4m class telescopes (UH88, UKIRT, IRTF, CFHT) aligned around the caldera in a semi-circle with an 800m diameter, providing good $u-v$ plane coverage. The 30m TMT will likely be built at the 13N site below the summit, 2.4km away, providing 40μarcsecond resolution.

Finally and maybe more conjecturally, the 39m ELT is currently being built on Cerro Armazones, 21km away from the four 8m VLT telescopes on Cerro Paranal. The geometric mean implies the sensitivity of a 25m diameter telescope but with a 5 μarcsecond resolution!

The expected resolution of these arrays is shown on Figure 1. We can also get a rough estimate of sensitivity of large arrays coupled interferometrically if we simply assume as a first approximation that the SNR is proportional to the collecting area, although this is not strictly true due to the geometrical ratio of different size telescopes as well as redundant baselines co-additions. Nonetheless under this assumption we then use our Calern results (Guerin et al. 2018) and normalize them for a SNR of 5 in one night of observing, and optimistically assuming 5000 spectral channels. The Ohana array would have a limiting magnitude of 11.2 and provide resolution between 0.25mas and 0.5mas (for 400nm to 900nm respectively). Adding the TMT would increase the limiting magnitude to 13.1 and with a resolution of 40 micro-arcseconds. Similar resolutions would be achieved by the GMT coupled with the Magellan telescopes, with a limiting magnitude of 12.3. Finally, the VLTs and the ELT, would provide a limiting magnitude of 13.6.

2.2 Astrophysical cases

Such resolutions on relatively bright objects at short wavelengths imply that the scientific applications will be focused on hot, compact, high surface brightness objects, such as White Dwarfs and X-ray binaries, as well as the BLR and accretion disk of active galactic nuclei (quasars and Seyfert 1 especially).

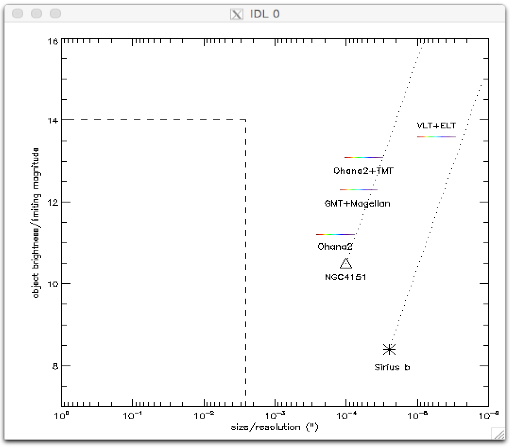

Fig. 1. Resolution versus expected sensitivity is shown for the various arrays with the spectrum showing the wavelength dependence. Sources below and to the left of the horizontal lines will be observable. The dashed rectangle on the left side of the plot shows the current limits of amplitude interferometry (although the limiting magntiude of VLTI is expected to increase to $\text{mag}_K \sim 18$ with the Gravity+ project). Also show on the plot is the brightness and expected size (or upper limit) of the closest know White Dwarf, Sirius-b (star), and of a Seyfert 1 nucleus (triangle), and the distance modulus extrapolation (dotted line) for such objects.

An upper limit of the apparent size of the nucleus of NGC 4151 was obtained by the Keck interferometer (Swain et al. 2003) with an 85m baseline in the near infrared (resolution ∼5mas). But if we consider that the size of an accretion disk should be on the order of 10^{-2}pc, at the distance of NGC4151 (19Mpc) this corresponds to an apparent size of 100μarcseconds; we note in passing that the K magnitude of the nucleus is ~ 9 while it is fainter in the visible (V∼12), so a compromise may be required in terms of resolution versus sensitivity for such objects, which we have plotted on Figure 1, as well as its distance modulus extrapolation for fainter, more distant objects. We can see that a Maunakea or Las Campanas intensity interferometer would be extremely well suited for the study of compact extragalactic sources.

The closest known White Dwarf, Sirius-b is expected to have a diameter on the order of 10^4km; at a distance of 8.6 light years, this translates to an apparent diameter of a few tens of μarcseconds, well within reach of the ELT–VLT baseline described above.

3 Spectral multiplexing

The first and simplest way to disperse the output of a multimode fiber and to couple it to a linear array of SPADs using a lenslet array. The dispersive element could be a prism (low-res), line grating (medium-res) or Volume Phase Holographic (VPH) grating (hi-res). Being fiber fed, the spectrograph can be made gravity invariant which helps with stability. Although simple in concept, the spectral resolution is limited unless such a spectrograph becomes large (we currently use a 1nm filter in front of the SPADs), making it sensitive to telescope environment (e.g. stability versus temperature). Such concepts are depicted on Figure 2.

An extension of this concept is to use a photonic lantern to split the multi-mode fiber into several single mode fibers which can be aligned in a pseudo-entrance slit in a V-groove. Although we currently do not have much experience with photonic lanterns, we suspect that they are preferable to adaptive optics due to the short wavelengths used in intensity interferometry. The main advantage here is in terms of compactness, since a single mode, bulk optics spectrograph can then be used. Furthermore a curved grating (and/or cross disperser) can be used to superpose the output of the different single mode fibers in the entrance slit onto the SPADs. Another advantage is that the optical parameters can be adjusted as new detectors become available and using 2D arrays, thousands of spectral channels appear feasible.

Finally, a fully integrated optics spectrograph is also worth mentioning since components exist and could in principle be duplicated or stacked into a very compact configuration. Figure 3 shows what such a device could look like: a multimode fiber is split into several single mode fibers (the exact number will depend on the D/r_0, or number of modes to be coupled into the spectrograph), each one feeding an Array Wave Guide (AWG) spectrograph; these devices are commercially available at near-IR wavelengths but nothing prevents an

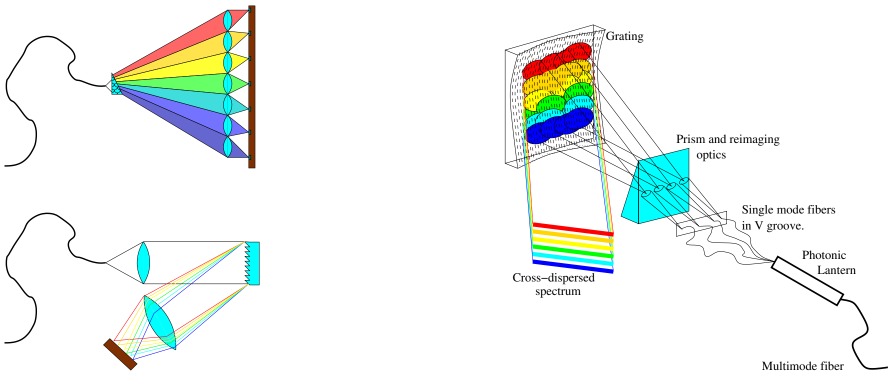

Fig. 2. Left: Conceptual spectrograph using a prism (left) or grating/VPH (right), fed by a multi-mode fiber. Although simple in design, the main issue with such concepts are the size and the stability. **Right**: Using a photonic lantern and a V-groove to align the single mode fibers into a pseudo slit, a single mode, bulk optics spectrograph can be used, allowing for a more compact design.

extension to shorter wavelengths. The monochromatic outputs of each AWG are then recombined (incoherently) using inverted photonic lanterns so that only one detector is required per wavelength.

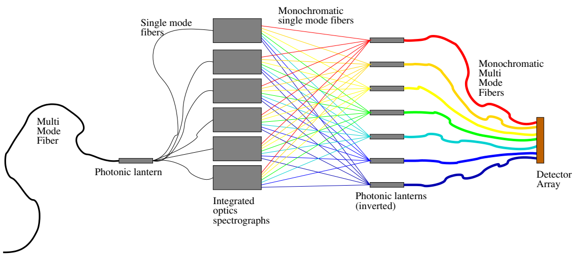

Fig. 3. Fully integrated optics spectrograph. See text for details.

The number of AWGs is determined by number of modes in the input photonic lantern and the number of inverse photonic lanterns is equal to the number of spectral channels, but we note that a custom device could integrate all these functions in a single optical chip. The main advantage here is that the beam never needs to come in or out of waveguides, the devices can be made very compact, and would be easy to maintain in temperature. We point out that a reliable, stable and completely autonomous device will be highly valuable when we try to operate several of these devices at telescopes kilometers away!

4 Conclusions

Intensity Interferometry seems very well matched to photonics techniques, especially to achieve double digit limiting magnitudes. As we pointed out, these high resolution spectrographs will need to be operated simultaneously (autonomously) many kilometers apart, requiring a high level of reliability and stability. We have started discussions to build a demonstrator for testing at the C2PU telescopes (Observatoire de la Côte d'Azur, Calern site), but we still need to find right level demonstrator between available technology (detectors, especially with SNSPDs becoming more attractive) and scalability. A sound first step would be to demonstrate that we can achieve an effective gain in sensitivity proportional to the square root of the number of spectral channels.

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