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Increasing the Signal-to-Noise Ratio in Intensity Interferometry

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ABSTRACT

Context. Intensity interferometry was developed in the 1950s by Hanbury-Brown and Twiss, but has not been broadly adopted in astrophysical research due to its low signal-to-noise ratio.
Aims. We developed an instrumentation technique to retrieve significant gains in the signal-to-noise ratio in intensity interferometry and explicitly resolve temporal photon bunching.
Methods. We perform narrowband spectral filtering on broadband starlight and measure the second order correlation using actively quenched avalanche photon detectors.
Results. We compare the the intensity interferometric measurements at various levels of spectral filtering to illustrate the corresponding increase in the signal-to-noise ratio and the implications for astronomy.
Conclusions. By increasing the signal-to-noise ratio by 2 to 3 orders of magnitudes above existing astronomical standards, stellar intensity interferometry may be seeing a revival boosted by such a technique, opening up many applications into quantum astronomy.

Key words. instrumentation: interferometers – radiation mechanisms: thermal – techniques: interferometric –

1. Introduction

1.1. What is intensity interferometry?

Hanbury-Brown & Twiss (1954, 1957) demonstrated that at sufficiently short baselines or timescales, both spatial and temporal correlation measurements of thermal light sources such as the stars should exhibit a photon bunching signal, or the $g^{(2)}$ second order correlation (Glauber 1963), that peaks at twice the value of the statistically random noise floor, such that

$$g^{(2)} = 1 + V^2. \tag{1}$$

where the visibility V is the modulus of the $g^{(1)}$ first order correlation. This behaviour is the basis for intensity interferometry (Hanbury-Brown 1974).

The temporal $g^{(2)}(\tau)$ reveals the characteristic emission mechanism of its source, while the spatial $g^{(2)}(b)$ imparts information about the shape and intensity distribution of the light source (Morgan & Mandel 1966; Mandel & Wolf 1995; Loudon 2000; Saleh & Teich 2007). This method was used by Hanbury-Brown & Twiss (1956, 1974) to measure the angular diameters of stars, with the additional benefit of being insensitive to first order noise contribution from urban light pollution and atmospheric turbulence (Dravins & LeBohec 2007).

1.2. Why is it not a standard technique in astronomy?

There has been a growing interest in recent years to revive the Hanbury-Brown–Twiss method (Dravins et al. 2005; Ofir & Ribak 2006; LeBohec et al. 2008; Millour 2008; Barbieri et al. 2009; Borra 2013), which has the potential to map the spatial structure of stellar formations (Millour 2009; Dravins et al. 2013), detect exoplanets (Hyland 2005; Strekalov et al. 2013), measuring the doppler-broadened linewidth of stellar sources of laser emissions (Dravins & Germanà 2008), and to test various models of quantum gravity (Lieu & Hillman 2003; Ng et al. 2003; Ragazzoni et al. 2003; Maziashvili 2009).

However, the low Signal-to-Noise Ratio (SNR) of such measurements have made it practically untenable in astronomical research applications, as suggested in Fig. 1.

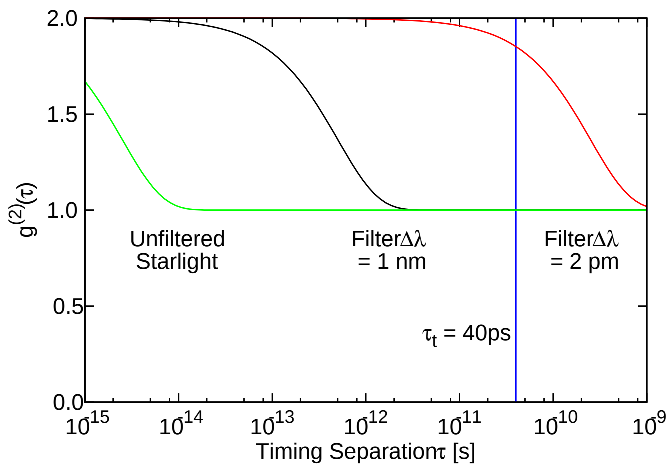

Fig. 1. Behaviour of temporal $g^{(2)}(\tau) = 1 + e^{\frac{-2|\tau|}{\tau_c}}$ for different photon coherence time τ_c. Green: $\tau_c \approx 5$ fs for unfiltered starlight, Black: $\tau_c \approx 1$ ps for passing through a typical narrowband interference filter, Red: $\tau_c \approx 0.5$ ns through our spectral filter setup. Blue vertical reference line indicates limit of photon detector resolution τ_t. The mismatch between the photon coherence time τ_c with the detector bandwidth τ_t strongly reduces the measurable thermal photon bunching signal (Scarl 1968).

We propose that optical spectral filtering may significantly increase the Signal-to-Noise Ratio of stellar intensity interferometric measurements towards useful levels, which shall be elaborated in the following section.

2. Signal-to-Noise Ratio

The feasibility of the intensity interferometry technique as a standard measurement tool for astronomical research depends on its Signal-to-Noise Ratio, as that constrains the extent of usable information that can be extracted within a reasonable timeframe and financial resources.

Over the decades, efforts to improve the Signal-to-Noise Ratio by increasing the detector bandwidth and telescope aperture size has been limited by technical and budgetary constraints.

There has been a lack of attempts in increasing the Signal-to-Noise Ratio using spectral filtering, as there is a long-held understanding since Hanbury-Brown (1974) that the Signal-to-Noise Ratio of intensity interferometry is independent of the optical bandwidth being measured and so consequently independent of any spectral filtering.

2.1. Standard interpretation: the Signal-to-Noise Ratio is independent of optical bandwidth

Defining the Signal-to-Noise Ratio (SNR) as (Hanbury-Brown 1974; Foellmi 2009; Rou et al. 2012; Malvimat et al. 2013):

$$SNR = A\eta R n V^2 \sqrt{\frac{T}{2\tau_t}} \tag{2}$$

where A = area of collection aperture, η = detector quantum efficiency, R = overall reflectivity for optical losses, n = source spectral density, V = visibility or the modulus of the complex degree of coherence, T = total measurement duration or integration time, τ_t = detector timing resolution or inverse of the electronic bandwidth.

The terms $A\eta Rn$ contribute to the total number of photons, N, collected for measurement.

It is argued that particularly in the regime of $\tau_c << \tau_t$, the action of spectral filtering will increase V^2 by a factor that is exactly negated by a corresponding decrease in total number of photons N measured. Thus under this consideration, the Signal-to-Noise Ratio is obviously independent of spectral filtering.

As such, efforts and concepts so far to increase the Signal-to-Noise Ratio of intensity interferometric measurements are focused into increasing A: ever larger aperture telescopes, n: targeting hotter stars, T: longer measurement windows and τ_t: high bandwidth photon detectors. However there are practical limits due to technology and budget which has stagnated experimental improvements via this approach.

2.2. Our interpretation: the Signal-to-Noise Ratio can be increased by reducing the optical bandwidth

It is important to note however that the spectral density of thermal blackbody radiation is defined by Maxwell-Boltzmann statistics. The blackbody power spectral density $dP/d\nu$ is expressed in terms of the power per unit frequency per spatial mode, where ϵ is the blackbody emissivity and assumed to be unity for an ideal blackbody (Stokes 1994):

$$\frac{dP}{d\nu} = \frac{\epsilon h\nu}{e^{h\nu/k_B T} - 1} \tag{3}$$

and making the approximation:

$$\frac{dP}{d\nu} \approx \frac{\Delta E}{\Delta\nu} = \frac{N_{th} h\nu}{\Delta\nu} \tag{4}$$

where ΔE is the sum photon energy available per unit time per spatial mode, and N_{th} is the number of photons available per unit time per spatial mode. The blackbody spectrum is smooth and continuous, thus within a relatively spectral range, allows for approximating the narrowband power spectral averaging to the power spectral gradient.

This allows us to express the spectral density n (number of photons s^{-1} Hz^{-1}) as follows:

$$n = \frac{1}{e^{h\nu/k_B T} - 1} = N_{th} \cdot \tau_c \tag{5}$$

where photon coherence time $\tau_c = 1/\Delta\nu$ with $\Delta\nu$ being the frequency spectral bandwidth (FWHM).

Thus the coherence time τ_c term is extracted from the Signal-to-Noise Ratio expression, therefore revealing the optical bandwidth dependence which was previously not explicit.

The total number of photons that is actually collected for measurement, N, must be reduced due to coupling losses, detector efficiency and telescope aperture mode matching to the stellar coherent length, such that:

$$N = N_{th} \cdot A\eta R < N_{th} \tag{6}$$

There are two other practical considerations: firstly, detectors have dead-time which exceeds the photon coherence time. Therefore, in order to perform an intensity interferometric measurement, which is essentially a two-photon coincidence measurement (Beck 2007; Naletto et al. 2009):

$$g^{(2)} = \frac{N_{12}}{N_1 N_2} \frac{T}{\tau_t} \tag{7}$$

it becomes necessary to split the N photons into two detectors, preferably balanced such that $N_1 = N_2 = N/2$. Thus the N dependence becomes:

$$N = 2\sqrt{N_1 N_2} \tag{8}$$

The second practical consideration is that the photon coincidences must occur in N_{11}, N_{12}, N_{21} or N_{22} pairs. However, since only one photon pairing option is measurable in any single experimental configuration, this contributes another factor of 1/4.

Finally, taking all these terms into consideration, the resultant Signal-to-Noise Ratio then takes the form as stated by Capraro et al. (2009):

$$SNR = V^2 \frac{\tau_c}{2} \sqrt{N_1 N_2} \sqrt{\frac{T}{2\tau_t}}. \tag{9}$$

In this representation, it should be clear that the action of spectral filtering will increase the coherence time τ_c by the same factor as the reduction in total number of photons measured in $\sqrt{(N_1 N_2)}$, thus mutually cancelling out any effect.

Therefore as illustrated in Fig. 2. in the regime of $\tau_c << \tau_t$ with no or little spectral filtering, V^2 approaches 0 and the Signal-to-Noise Ratio is both practically independent of spectral filtering and also too low to be useful in astronomy applications.

However, in the regime of very narrowband filtering such that $\tau_c >> \tau_t$, although the coherence time τ_c and total number of photons measured still mutually cancel, the V^2 or $g^{(2)} - 1$ increases greatly and approaches 1, thus making the Signal-to-Noise Ratio both dependent on spectral filtering, and extracting significant gains as a result.

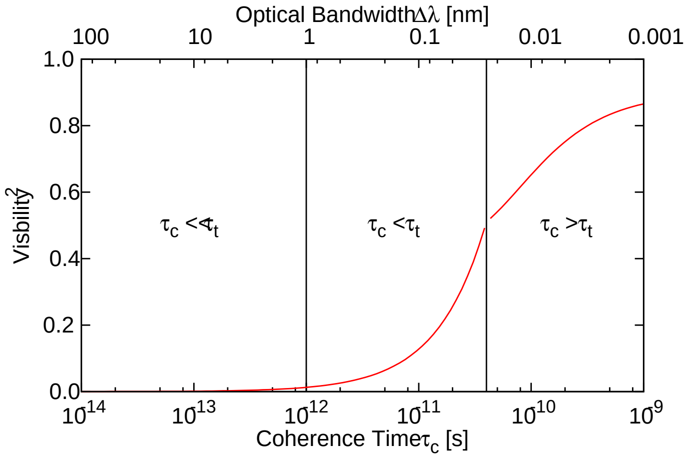

Fig. 2. Upper bound estimates for the measurable visibility with varying degrees of spectral filtering and thus photon coherence time τ_c. Photon detector bandwidth $\tau_t = 40$ ps.

3. Blackbody Spectral Filtering

not to repeat too much data/material from blackbody paper?

3.1. Experimental Scheme

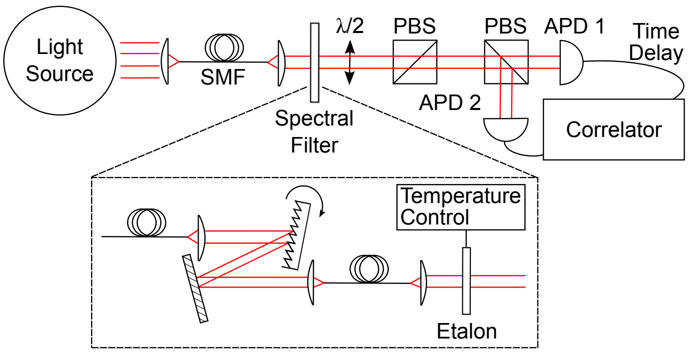

Fig. 3. Setup to determine the temporal correlation $g^{(2)}(\tau)$ for wideband thermal light. The initial spectrum gets filtered to a narrow optical bandwidth such that the temporal decay of the second order correlation function can be observed with conventional single photon detectors in a Hanbury-Brown–Twiss experiment. We employ a combination of a grating and a temperature-tuned etalon as a spectral filter, and ensure spatial coherence in the setup by using single mode optical fibers (SMF).

The thermal light from the arc lamp is coupled into the setup via optical fiber. We spatially filter the light by a single mode fiber into a single Gaussian transverse mode for optimal performance with the diffraction grating and etalon. The Sunlight is then spectrally filtered by a solid etalon of bandwidth 2 GHz. The diffraction grating selects one of the transmission modes of the etalon centered around 546.1 nm. The Glan-Taylor polarizer transmits only linearly polarized light and in conjunction with the half-wave plate, allows us to both balance the detector count rates and to compensate for birefringence in the setup, thus minimizing the duration of data collection.

We use an argon arc lamp to provide the continuous spectrum of a incoherent thermal light source. It has an effective blackbody temperature of around 6000 K, and thus a suitable analogue to the Sun.

3.2. Measurable Gains in Solar Signal-to-Noise Ratio

Solar $g^{(2)}(\tau)$ measurement, $T = 85$ min, $N_1 = N_2 = 110000\ s^{-1}$, $\tau_t = 40$ ps, $V^2 = 0.37$, $\tau_c = 0.32$ ns. SNR after filtering is 52. If we scale down accordingly, unfiltered SNR is in the regime of 0.01.

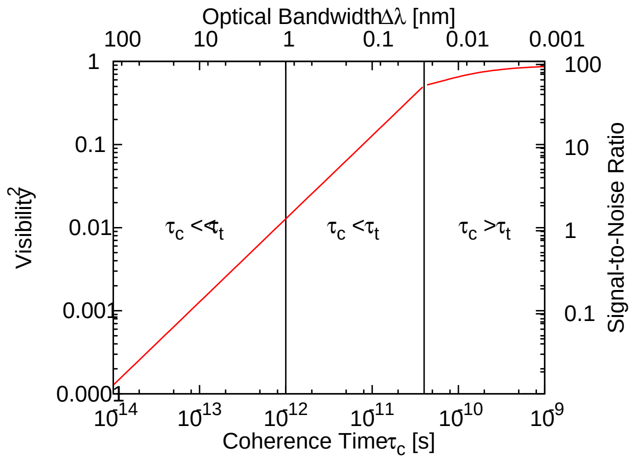

Fig. 4. Theoretical upper bound estimates of the Signal-to-Noise Ratio of an intensity interferometric measurement at various degree of spectral filtering, given the experimental parameters of the Solar $g^{(2)}\tau)$ measurement.

4. Discussion and Applications

1. Wolf Rayet stars like Eta Carinae or Gamma Velorum with suspected doppler laser emission with line width of about 30 MHz. Similar to laser with rotating ground glass, to measure g2 and observe greater than 2 plus thermal g2. fourier transform to reveal the line width of the laser, i.e. check whether we observe a temporal g2 with coherence time of $\approx 30\,\mu s$.

2. Quantum gravity models test via measuring photon decoherence as a function of redshift and cosmic distances. Test for planck time and quantum space-time foam. fit for alpha.

3. Measuring stellar angular diameter, either cheaper faster or more precise than original HBT and existing methods. By measuring at baseline = 0 m and maybe 2 m, and with these renormalised and curve fit with bessel function first order first kind and via the spatial frequency determine the stellar angular diameter.

4. Measuring stellar angular diameter at XY axes as a measure of oblateness, and thus information as to the rotational behaviour of the stars. double act of step 3.

5. Measuring the stellar angular diameter of cepheid variables over time, and thus determine its rate and magnitude of pulsation which by its periodicity, have a consistent relationship with its luminosity, and thus useful as a standard candle to gauge cosmic distances. multiple acts of step 3, over time.

6. By measuring secondary spatial g2 peaks, magnitude and/or reverse fourier transform to retrieve the intensity profile of the stellar surface and thus its limb darkening coefficient, which is useful to both further understanding stellar internal dynamics and tighten constraints in exoplanent detection via luminosity transit.

7. By measuring oscillation in the secondary spatial g2 peaks, detect exoplanetary transits.

8. Verify pairs of object suspected to be mirror images due to gravitational lensing, i.e. to find a g2 signal rather than comparing photos of shape and intensity and spectral distribution.

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References

Barbieri, C., Daniel, M. K., de Wit, W. J., et al. 2009, Astro2010: The Astronomy and Astrophysics Decadal Survey, 2010
Beck, M. 2007, J. Opt. Soc. Am. B, 24
Borra, E. F. 2013, MNRAS
Capraro, I., Naletto, G., Barbieri, C., et al. 2009, in Proceedings of Science: Quantum of Quasars workshop, creative Commons Attribution-NonCommercial-ShareAlike Licence
Dravins, D., Barbieri, C., Deppo, V. D., et al. 2005, QuantEYE: Quantum Optics Instrumentation for Astronomy, oWL Instrument Concept Study
Dravins, D. & Germanà, C. 2008, in The Universe at sub-second timescales, ed. D. Phelan, O. Ryan, & A. Shearer, AIP
Dravins, D. & LeBohec, S. 2007, Proc. SPIE, 6986, 698609
Dravins, D., LeBohec, S., Jensen, H., Nuñez, P. D., & for the CTA Consortium. 2013, Astroparticle Physics, 43, 331, elsevier
Foellmi, C. 2009, A&A, 507, 1719, eSO
Glauber, R. 1963, Phys. Rev., 131, 2766
Hanbury-Brown, R. 1974, The intensity interferometer: its application to astronomy (London : Taylor & Francis ; New York : Halsted Press), 184
Hanbury-Brown, R. & Twiss, R. Q. 1954, Phil. Mag., 45, 663
Hanbury-Brown, R. & Twiss, R. Q. 1956, Nature, 178, 1046
Hanbury-Brown, R. & Twiss, R. Q. 1957, Proc. Roy. Soc., A242, 300
Hanbury-Brown, R. & Twiss, R. Q. 1974, MNRAS, 167, 121
Hyland, D. 2005, Proc. SPIE, 5905: Techniques and Instrumentation for Detection of Exoplanets II, 590511
LeBohec, S., Barbieri, C., de Wit, W.-J., et al. 2008, Proc. SPIE, 7013: Optical and Infrared Interferometry, optical and Infrared Interferometry
Lieu, R. & Hillman, L. W. 2003, ApJ, 585, L77
Loudon, R. 2000, The Quantum Theory of Light (Oxford Science Publications)
Malvimat, V., Wucknitz, O., & Saha, P. 2013, MNRAS
Mandel, L. & Wolf, E. 1995, Optical Coherence and Quantum Optics (Cambridge University Press)
Maziashvili, M. 2009, Astroparticle Physics, 31, 344
Millour, F. 2008, New Astronomy Reviews, 52, 177
Millour, F. 2009, RevMexAA, The interferometric view on Hot stars
Morgan, B. L. & Mandel, L. 1966, Physical Review Letters, 16, 1012
Naletto, G., Barbieri, C., Occhipinti, T., et al. 2009, A&A, 508, 531, eSO
Ng, Y. J., Christiansen, W. A., & van Dam, H. 2003, ApJ, 591, L87
Ofir, A. & Ribak, E. N. 2006, Proc. SPIE, 6268: Advances in Stellar Interferometry
Ragazzoni, R., Turatto, M., & Gaessler, W. 2003, ApJ, 587, L1
Rou, J., Nunez, P. D., Kieda, D., & LeBohec, S. 2012, MNRAS, 000, 1
Saleh, B. E. A. & Teich, M. C. 2007, Fundamentals of Photonics (John Wiley & Sons)
Scarl, D. B. 1968, Phys.Rev, 175, 1661, issue 5
Stokes, L. F. 1994, IEEE Circuits and Devices Magazine, 10, 46
Strekalov, D. V., Erkmen, B. I., & Yu, N. 2013, Phys. Rev A, 88, 9