Contrast and phase closure acquisitions in photon counting regime using a frequency upconversion interferometer for high angular resolution imaging

D. Ceus,¹ L. Delage,¹ L. Grossard,¹ F. Reynaud,^{1*} H. Herrmann² and W. Sohler²

¹Xlim Photonique Department, UMR CNRS 7252, 123 av. Albert Thomas, F-87000 Limoges, France ²Universität Paderborn, Angewandte Physik, Warburger Str. 100, D-33098 Paderborn, Germany

Accepted 2012 December 17. Received 2012 December 17; in original form 2012 July 11

ABSTRACT

In the context of new generation instruments for astronomical interferometer, we have developed in laboratory a new kind of optical interferometer using the frequency conversion of the star light. We investigate the sensitivity limit and reliability of our so-called upconversion interferometer when operating in photon counting mode. For this purpose, we have implemented a laboratory test bench including two three-arm interferometers dedicated to high angular resolution imaging. The first classical one works at the same wavelength as the laboratory star (infrared) and operates with high optical flux levels (used as a reference interferometer). The second one, under test, uses sum frequency generation process in a non-linear optical waveguide placed on each arm to shift the wavelength of the infrared laboratory star to the visible domain. The observables are obtained in photon counting operation, involving signal processing to recover unbiased data. The reference measurement (high flux complex visibilities in infrared) and the upconversion interferometer observables (complex visibilities obtained in photon counting regime) are in good agreement. We notice a degradation on the phase closure terms reliability for low values of the triple product (bispectrum). We estimate from the experimental results the related limiting magnitude for several configurations using an upconversion interferometer.

Key words: instrumentation: interferometers – methods: laboratory – techniques: miscellaneous.

1 INTRODUCTION

In astronomy, the aperture synthesis technique is a powerful way to reach high angular resolution through the analyse of the collected optical fields cross-correlation. Multi-aperture telescope arrays, such as Center for High Angular Resolution Array (CHARA), Very Large Telescope Array (VLTI) or Navy Optical Interferometer (NOI), allow us to access to nanoradian angular resolution at a 1 µm wavelength operation. The observables acquired with these interferometers are used for a model fitting or processed by an image restoration algorithm to estimate the angular intensity distribution of the observed object (Renard, Thiébaut & Malbet 2011; Baron 2012). The low level of collected flux associated with the global optical losses of the instrument leads to the detection of very weak levels of light. In the visible domain, the measurements of these observables can be achieved in photon counting regime (Bonneau et al. 2010). Our team has worked for a few years on a cost-effective

* E-mail: francois.reynaud@xlim.fr

technique that brings the advantages of using the efficient photoncounting detectors, the spatial filtering devices and the low optical loss beam transport components, for infrared radiations (mediuminfrared or far-infrared). Our technique is based on the frequency conversion of star light from the infrared to wavelengths where more efficient optical components and detectors are available (nearinfrared and visible). Before applying the frequency conversion technique to a real interferometer, several steps must be validated to ensure that the frequency conversion process preserves reliable acquisitions of the observables and can thus lead a proper image reconstruction.

For this purpose, we have developed a high angular resolution interferometer laboratory breadboard where the upconversion [sum frequency generation (SFG) process] is simultaneously applied on each interferometric arm. The first experiments carried out with our so-called upconversion interferometer were dedicated to the measurement of the fringes contrasts (Brustlein et al. 2008) and the phase closure (Ceus et al. 2011). These experiments showed a perfect agreement between an upconversion interferometer and a classical acquisition of the observables. As first steps, these experimental studies were achieved in a high flux level configuration. Over this proof of principle study, the infrared wavelength to be converted has been selected in order to take advantage of the mature and available technologies at 1.55 μ m. These results in nearinfrared could be extrapolated to medium-infrared and far-infrared, thanks to the development of dedicated SFG devices. This point is not addressed in the present paper.

In this article, we present the implementation of an upconversion interferometer operating in photon counting mode. This step is mandatory to evaluate the limits of detection of an upconversion interferometer and to prove the reliability of this new kind of instrument in a real astronomical configuration.

Section 2 recalls some basic knowledge on the observables to be acquired with an interferometer in high level and in photon counting regime, and the properties of our frequency conversion device. Section 3 reports on the description of the experimental set-up used for this study. Then, from our experimental results, we estimate the limiting magnitude reachable with a 1-m, a 2-m and an 8-m class mirror used in a three-telescope array.

2 GENERAL INFORMATION

2.1 Observables to be acquired with an astronomical interferometer

An astronomical interferometer is dedicated to provide information on the spatial intensity distribution of the optical target through the acquisition of the interferometric fringes. The reliability of these measurements makes necessary the use of a steady interferometer calibrated on a reference object. In this framework, uncontrolled differential defaults (chromatic dispersion, polarization, intensity level...) between the interferometric arms have to be minimized to avoid a loss of information. To prevent these problems, the interferometer shall be designed with spatial filtering components (Froehly 1981; Coudé du Foresto 1997), polarization maintaining components and chromatic dispersion balanced interferometric arms (Delage & Reynaud 2000). The data processing has to include an accurate measurement of the photometric level at the output of each interferometric arms to take into account the photometric contribution to the global contrast. The instruments FLUOR (Fiber Linked Unit for Optical Recombination; Coudé du Foresto et al. 1996a), IONIC (Integrated Optics Near-infrared Interferometric Camera; Berger 2003), PIONIER (Precision Integrated-Optics Near-infrared Imaging ExpeRiment; Le Bouquin et al. 2011) and AMBER (Astronomical Multi BEam Recombiner; Petrov et al. 2007) comply with most of these requirements. Fig. 1 shows an example of schematic drawing of an astronomical interferometer in a three-telescope configuration. The light coming from the astronomical target is collected by the telescope array. The optical fields propagate along the interferometric arms passing through the delay lines (DLs) to equalize the optical paths. Light beams propagate in a set of single-mode and polarization maintaining optical fibres and couplers (integrated components or optical fibre devices). The fringe pattern can be observed in the spatial or temporal domain. In our experimental set-up, we used a temporal display of the interferometric signal. This principle is described in Fig. 2 in the case of non-redundant temporal optical path modulations. The accurate control of the optical path length modulation between the interferometric arms allows us to choose the number of fringes per frame related to a pair of telescopes. At the output of the optical coupler, the temporal interferometric pattern, called I(t), is detected. Its mathematical expression is



Figure 1. Schematic drawing of a three-arm astronomical interferometer. T_i is the *i*th telescope, and b_{ij} is the baseline between the T_iT_j pair of telescopes. φ_i is the phase term due to the atmospheric turbulence, linked to the T_i telescope. OPM: optical path modulator and DL: delay line.



ر سفية pmain. c arms es.

Downloaded from http://mnras.oxfordjournals.org/ at Universitaetsbibliothek Giessen on June 20, 2015

Figure 2. Acquisition of the interferometric signal in the temporal domain. The optical path difference modulations between the interferometric arms allow us to encode separately the fringes related to a pair of telescopes.

given by

$$I(t) = I_1 + I_2 + I_3$$

+2\sqrt{I_1I_2}C_{12}\cos(mod_{12}(t) + \varphi_{12} + \varphi_2 - \varphi_1)
+2\sqrt{I_2I_3}C_{23}\cos(mod_{23}(t) + \varphi_{23} + \varphi_3 - \varphi_2)
+2\sqrt{I_3I_1}C_{31}\cos(mod_{31}(t) + \varphi_{31} + \varphi_1 - \varphi_3), (1)

where I_i is the flux in the interferometric arm *i*, C_{ij} and φ_{ij} are the fringe contrast and the phase terms of the complex visibility, respectively, measured for a pair of telescopes T_iT_j . $mod_{ij}(t) = 2\pi f_{ij}t$ is the temporal modulation with $f_{12} \neq f_{23} \neq f_{31} \neq 0$ the fringe number, respectively, related to the T_1T_2 , T_2T_3 and T_3T_1 pair of telescopes. φ_i , related to a T_i telescope, is a random phase term due to the atmospheric turbulence or mechanical vibrations along the interferometric arm *i*.

The observables are the complex visibilities (V_{ij})

$$V_{ii} = C_{ii} \exp^{j\varphi_{ij}}.$$
(2)

The Zernike Van Cittert theorem (see Born & Wolf 1980 for details) yields a Fourier transform (FT) relation between the complex visibility of the interferences and the spatial spectrum of the angular distribution $O(\Omega)$ of the observed object, with Ω the angular direction. In the case of a temporal acquisition of the interferometric pattern, the observables are extracted through a FT of I(t), written as $\tilde{I}(f)$. For a high level signal, assuming there is no significant noise, $\tilde{I}(f)$ is expressed as

$$\tilde{I}(f) = (I_1 + I_2 + I_3)\delta(f) + \sqrt{I_1 I_2 V_{12} \delta(f - f_{12})} \\
+ \sqrt{I_2 I_3 V_{23} \delta(f - f_{23})} \\
+ \sqrt{I_3 I_1 V_{31} \delta(f - f_{31})},$$
(3)

where δ denotes the Dirac distribution function. Fig. 2 shows the temporal interferometric signal and its related normalized FT.

The acquisition of the complex visibilities with an optical interferometer is corrupted by a random phase distortion (φ_i) (see equation 1) due to the atmospheric turbulence and/or the instrument vibrations. The phase of the object spectrum related to one visibility cannot be directly retrieved. Jennison's phase closure technique (Jennison 1958) allows us to extract a phase information exclusively concerning the object spectrum. For this purpose, a linear combination of phase terms equal to ϕ is measured. For a three-arm interferometer, the product of the three experimental complex visibilities V_{12} , V_{23} and V_{31} related to the pair of telescopes T_1T_2 , T_2T_3 and T_3T_1 , respectively, yields the phase closure

$$\phi = (\varphi_1 - \varphi_2 + \varphi_{12}) + (\varphi_2 - \varphi_3 + \varphi_{23}) + (\varphi_3 - \varphi_1 + \varphi_{31})$$

= $\varphi_{12} + \varphi_{23} + \varphi_{31}.$ (4)

Our test bench is dedicated to the measure of C_{ij} and ϕ extracted from the interferometric signal. We achieved the acquisition of the interferometric signal in two optical intensity levels as represented in Fig. 3. The first one (top curve), previously called I(t), is acquired with high optical flux level, for which the photon noise is nonsignificant. Reaching the photon counting mode (bottom curve), the interferometric signal, called D(t), is a digital acquisition of photo-events. Contrary to the high flux level, the FT of D(t) is now corrupted by a white noise called photon noise. Photon noise



Figure 3. Interferometric signals and related spectrum modulus for high flux level signal (I(t)) (top) and the photon counting signal (D(t)) (bottom). The photon noise induces a quantized intensity detection and a background noise in the spectrum.

must be taken into account to extract reliable complex visibilities in photon counting regime.

The expression of the uncorrected contrast is

$$C_{ij}^{u} = \frac{1}{K_{ij}} \sqrt{\left\langle \tilde{D}_{ij}^{(2)} \right\rangle_{N_f}},\tag{5}$$

where K_{ij} is a normalization factor depending on the bias correction and the photometric level of the interferometric arms, $\langle \rangle_{N_f}$ is the average operator applied to a number of N_f frames and $\tilde{D}_{ij}^{(2)}$ is the squared modulus of the FT[D(t)] related to a T_iT_j pair of telescopes. $\tilde{D}_{ij}^{(2)}$ is called the power spectrum of D(t). According to (Wirnitzer 1985) and Longueteau, Delage & Reynaud (2003), the corrected measurement of the contrast in photon-counting mode can be computed by

$$C_{ij}^{c} = \frac{1}{K_{ij}} \sqrt{\left\langle \tilde{D}_{ij}^{(2)} \right\rangle_{N_{f}} - \langle N_{m} \rangle_{N_{f}}}, \tag{6}$$

where $\langle N_m \rangle_{N_f}$ is the mean number of photons per frame. The expression of the uncorrected phase closure is

$$\phi^{u} = \arg\left[\langle \tilde{D}_{32,21}^{(3)} \rangle_{N_{f}}\right],\tag{7}$$

where $\tilde{D}_{32,21}^{(3)}$ is the bispectrum acquired in photon-counting regime. The corrected measurement of the phase closure term can be computed by

$$\phi^{c} = \arg \left[\langle \tilde{D}_{32,21}^{(3)} \rangle_{N_{f}} - \langle \tilde{D}_{21}^{(2)} \rangle_{N_{f}} - \langle \tilde{D}_{23}^{(2)} \rangle_{N_{f}} - \langle \tilde{D}_{31}^{(2)} \rangle_{N_{f}} + 2 \langle N_{m} \rangle_{N_{f}} \right].$$
(8)

2.2 Principle of the sum frequency generation

Through the interaction of different optical fields in a suitable nonlinear crystal, the SFG is a process which allows us to convert an infrared wave to the visible spectral range. We can notice that the use of this frequency conversion process has the fundamental property to be inherently noiseless (Louisell, Yariv & Siegman 1961; Smith & Townes 1969); sum frequency conversion is well suited for astronomical interferometry. The lithium niobate (LiNbO₃) crystal is a good candidate to achieve this conversion process. The LiNbO₃ has a window transparency ranging from 500 to 5000 nm, a strong nonlinear coefficient and a mature manufacturing technology (Nikogosyan 2005). By mixing a signal wave (at λ_s) with a pump wave (at λ_p) in the non-linear LiNbO₃ crystal, we can generate a converted wave at the sum-frequency according to

$$\frac{1}{\lambda_{\rm s}} + \frac{1}{\lambda_{\rm p}} = \frac{1}{\lambda_{\rm c}}.\tag{9}$$

An efficient frequency conversion occurs when the three copropagating waves are phase matched. This requirement is expressed by a relationship between the wavenumbers (k_i) in the propagation medium

$$\Delta k = k_{\rm c} - k_{\rm s} - k_{\rm p} = 0 \tag{10}$$

where $k_i = 2\pi n_i/\lambda_i$, with n_i (i = s, c, p) the refractive index depending on the propagation neutral axis of the birefringent non-linear medium. This way, the polarization orientation of the beams must be carefully chosen to comply with the phase matching relation (equation 10). In addition, an efficient conversion requires a strong confinement of the interacting optical fields over a long interaction length. This can be obtained by using single-mode waveguide to propagate the beams.



Figure 4. Simulation of the intensity evolution of the converted signal as a function of the source signal λ_s . Parameters of the simulation: PPLN-waveguide length = 4 cm, oven temperature=90°C, $\lambda_p = 1064$ nm and $\Lambda = 10.85 \ \mu m$.

In practice, we use a periodically poled LiNbO₃ (PPLN) with a specific poling period Λ , and we talk about the quasi-phase matching (Boyd 2008)

$$\Delta k_{\rm Q} = k_{\rm p} + k_{\rm s} - k_{\rm c} + \frac{2\pi}{\Lambda} = 0. \tag{11}$$

Judiciously choosing the doublet (λ_s, λ_p) allows us to take advantage of the converted signal of mature waveguide technologies such as optical fibres or integrated components. For our experimental principle demonstration, we choose a wavelength doublet ($\lambda_s =$ 1542 nm, $\lambda_p = 1.064$ nm). According to equation (9), the wavelength of the converted signal is $\lambda_c = 630$ nm. In this configuration, one infrared photon can be efficiently detected in the photon counting regime with a hybrid process including a wavelength change and an avalanche photodiode Silicon detection.

The frequency conversion efficiency η is given by

$$\eta = \frac{I_{\rm c}}{I_{\rm s}},\tag{12}$$

where I_s is the intensity of the source signal and I_c is the converted signal. The expression of I_c is theoretically given by

$$I_{\rm c} = K (2\pi\nu_{\rm c})^2 I_{\rm p} I_{\rm s} L^2 \left(\frac{\sin\left(\Delta k_{\rm Q} L/2\right)}{\Delta k_{\rm Q} L/2}\right)^2,\tag{13}$$

where *K* is a parameter related to the optical properties of the PPLN, I_p is the intensity of the pump source and *L* is the crystal length. Fig. 4 shows the theoretical evolution of I_c as a function of the signal source λ_s around 1 542 nm. The full width at half-maximum of this curve is the spectral acceptance ($\Delta\lambda$) of the PPLN (0.3 nm in our experimental configuration). Conclusively, for a quasimonochromatic pump source, $\Delta\lambda$ gives the spectral bandwidth of the source signal to be converted. Notice that the PPLN-waveguides are placed in an oven to adjust the temperature, and thus, the quasiphase matching condition.

2.3 Upconversion interferometer concept

Our proposal aims to insert an SFG module in each arm of a classical three-telescope interferometer in order to benefit from mature



Figure 5. Representation of one upconversion interferometric arm. The star light, collected by a telescope, co-propagates with the pump source by means of a multiplexer. Then, these optical fields are injected together in a non-linear crystal (PPLN-waveguide) placed in a temperature stabilized oven. The converted signal coming out from the waveguide passes through a spectral filtering stage and feed a single-mode optical fibre.

technologies concerning coherent transport and the photon counting detection after frequency conversion of the astronomical light. Recently, we showed that the use of an SFG module on a single arm of the interferometer has enough sensitivity to successfully convert the light of astronomical sources (Ceus 2012).

An overview of one upconversion arm is drawn in Fig. 5. By using a PPLN-waveguide, the frequency conversion can be achieved while providing a single-mode propagation and a polarization maintaining of the converted wave. These requirements are mandatory in an interferometric context where the goal is to acquire steady and well-calibrated fringes. The light collected by the telescope is mixed with a pump source by means of a multiplexer. Then, the optical fields are injected in a PPLN-waveguide where the SFG process takes place. At the output of this waveguide, the converted wave is collimated and reaches a spectral filtering stage to reject the residual pump source. After passing through a DL, the converted wave is injected in a 630 nm single-mode polarization maintaining optical fibre. The fields at the output of each interferometric arm are mixed together. The temporal interferometric pattern is acquired in the visible domain with an Si photon counting detector.

The whole upconversion interferometer is described in the following part. Working in photon counting mode, this configuration must be tested to evaluate the sensitivity limit of this new kind of instrument.

3 DESCRIPTION OF THE HIGH ANGULAR RESOLUTION UPCONVERSION INTERFEROMETER TEST BENCH

The experimental set-up, drawn in Fig. 6, can be split into four main subsystems:

(a) A star simulator: the test-object was a point-like source or a binary star with an adjustable photometric ratio.

(b) A telescope array: three telescopes in a one-dimensional linear configuration.

(c) An infrared interferometer: used as a reference interferometer with high flux level. This instrument, called Multi-Aperture Fibre Linked (MAFL) interferometer, has been used in a previous work (Olivier et al. 2007) and allows accurate and reliable measurements of complex visibilities with a 1550 nm wavelength radiation.



Figure 6. Whole experimental setup including the upconversion test bench used in photon counting mode and the infrared interferometer used in high flux level. DFB: Distributed Feedback laser at 1542 nm, CL: Collimating Lens, *nb* the baseline between a couple of telescopes $T_i T_j$ with *n* an integer and b = 16 mm, Mux: allows the combination of the signal at 1542 nm and 1064 nm, PPLN: Periodically Poled Niobate Lithium; MAFL: Multi-Aperture Fibre Linked Interferometer, T (°C): temperature controller, IF: Interference Filter at $\lambda = 630$ nm ± 20 nm, L: Lens, P: Prism. The DLs are used for precision optical path length control in the infrared and visible interferometers. The attenuators allow the upconversion interferometer to operate in the photon counting mode.

(d) An upconversion interferometer: instrument under test in photon-counting mode.

We can notice that the optical devices used in our experiment are spatially single-mode and based on polarization maintaining components at the operating wavelength(s). For our proof of principle experiment, we use telecommunication wavelength sources and components for availability and cost reasons. The star simulator (see Fig. 6 a) is either a point-like source used to calibrate the interferometer, or a binary star (with a μ -adjustable photometric ratio) used as a test object. For this purpose, the light emitted by a distributed feedback laser (DFB) ($\lambda_s = 1542 \text{ nm}$) feeds an adjustable 1 to 2 fibre coupler. Its first output feeds an optical switch, allowing us to turn on/off one of the two stars. The second output is connected to 500 m optical fibre longer than the 100 m coherence length of the DFB laser. This ensures the spatial incoherence of this binary star. The two fibre ends, glued on a Vgroove, are spaced by 27.9 µm and placed in the focal plane of a collimating lens with a 1900 mm focal length and a 190 mm diameter. The resulting characteristics of our laboratory object corresponds to two spatially incoherent pointlike stars with an $\Omega_0 = 14.7 \,\mu$ rad angular separation, an adjustable photometric ratio μ and the possibility to switch on/off one of the two stars. The angular intensity distribution of the two point-like sources can be written as

$$O(\Omega) = \delta(\Omega - \Omega_0/2) + \mu \delta(\Omega + \Omega_0/2).$$
(14)

The angular FT of equation (14) gives the object spectrum \tilde{O}

$$\tilde{O}(N) = \exp\left(-j\pi N\Omega_0\right) + \mu \exp\left(j\pi N\Omega_0\right),\tag{15}$$

where $N = bn_{ij}/\lambda_s$ is the spatial frequency related to the T_iT_j pair of telescopes. According to the Zernike Van Cittert theorem, the normalized visibility is expressed as

$$V_{\text{Normalized}} = \left| \frac{\tilde{O}(N)}{\tilde{O}(0)} \right| \exp\left(j \arg[\tilde{O}(N)] \right).$$
(16)

According to equations (15) and (16), the normalized contrast is

$$\frac{\tilde{O}(N)}{\tilde{O}(0)} \bigg| =$$

$$\frac{\sqrt{\left(\left(1+\mu\right)\cos\left(\pi N\Omega_{0}\right)\right)^{2}+\left(\left(\mu-1\right)\sin\left(\pi N\Omega_{0}\right)\right)^{2}}}{1+\mu}.$$
 (17)

From equation (15), the resulting phase can be written as

$$\arg[\tilde{O}(N)] = \arctan\left(\frac{\mu - 1}{\mu + 1}\tan(\pi N\Omega_0)\right).$$
(18)

The phase closure ϕ is derived from equation (4) according to equation (18). As can be seen, adjusting the photometric ratio between the two stars of the simulator (i.e. the μ -parameter) allows us to arbitrarily set the contrasts and the phase terms.

The three-telescope array (see Fig. 6 b) collects the optical light emitted by the binary star. A T_i telescope is composed of an achromatic doublet (f = 10 mm) feeding a spatially single-mode and polarization maintaining optical fibre located in its focal plane.

Fig. 7 shows several simulations of the contrast product and the phase closure terms for four configurations of our telescope array.

In our experiment, we choose the configuration where a T_1T_2 pair of telescopes is spaced by a $b_{12} = 16$ mm separation and a T_2T_3 by $b_{23} = 32$ mm. This configuration exhibits significant variation of the observables while adjusting the μ -parameter of the laboratory star. This configuration is convenient for testing the reliability of our measurements.

Temporal modulations of the optical paths are applied before the optical couplers that split the beams either to the infrared interferometer or to the upconversion interferometer. This way, the optical phase modulations are exactly the same for visible and infrared waves. These optical couplers are not balanced in intensity. This way, 90 per cent of the infrared signal is routed to the infrared



Figure 7. Simulation of the contrast triple product $(C_{12}C_{23}C_{31})$ and the phase closure (ϕ) plot as a function of the adjustable photometric ratio (μ) for several configurations of the three-telescope array.

interferometer (see Fig. 6 c) previously developed by our team for the MAFL interferometer project (Olivier et al. 2007). This infrared interferometer has demonstrated its accuracy and reliability for the acquisition of the contrasts and phase closure terms of an infrared object. It is used as reference.

The 10 per cent remaining of the infrared signal are attenuated through adjustable fibred attenuators, then the infrared light fed three identical optical frequency conversion benches.

Let us describe one of these frequency conversion benches in detail. The frequency conversion of the attenuated infrared wave is achieved in a PPLN-waveguide pumped by a 1 064 nm YAG laser. Notice that the pump source is shared out among the frequency conversion benches. Then, the infrared signal and the pump source are injected together in a 40 mm PPLN-waveguide with a 11.3 µm poling periodicity. Its temperature is stabilized at about 90°C. At the output of the PPLN, the optical waves pass through a spatial filtering stage used to separate the converted signal from the residual pump source. For this purpose, the converted signal is collimated and passes through a prism and an interference filter centred on the wavelength of the converted signal. Finally, the collimating beam is focused and injected in an optical fibred DL. A beam shutter, placed between the prism and the interference filter, allows us to switch on/off the converted signal. This way, it is possible to access the photometry on the arms of the upconversion interferometer by acting successively on the beam shutters.

The three upconverted optical fields are combined with an X-cube (Delage, Reynaud & Lannes 2000). This device has four inputs and four outputs. In our experimental configuration, it is used as a symmetrical 3 to 1 coaxial combiner, allowing us to display the interferometric pattern in the visible domain. The optical path lengths of the upconverted interferometric arms are equalized by adjusting the path length of the visible DL. The interferometric signals are detected with a silicon photon counting module characterized by a 60 per cent detection efficiency at 630 nm and a 164 Hz dark count average.

The raw data coming from the photon counting detector are acquired and processed to extract C_{ij}^u , C_{ij}^c , ϕ^u and ϕ^c . The adjustment of the optical fibre attenuators allows us to achieve the acquisition of the observables for different flux levels.

4 EXPERIMENTAL RESULTS

As seen previously, setting the μ -parameter of the star simulator changes the contrast and the phase closure terms. The observables are extracted from the interferometric signal measured in high flux level (with the infrared interferometer) and in photon-counting mode (with the upconversion interferometer).

Several steps are necessary to calibrate the upconversion interferometer.

(i) Photometry measurements on the interferometric arms with a bright point-like star.

(ii) Fringe acquisition and calibration of the observables with the bright point-like star used in step one.

(iii) Switch-on of the second point-like star.

(iv) Tune the attenuators to reach the expected photon-counting level.

(v) Photometry measurements on the interferometric arms with the two point-like stars.

(vi) For one μ parameter: acquisition of the contrasts and the phase closure terms.

(vii) Change the μ parameter, switch-off one star, then back to step one.

The contrasts and phase closure terms are extracted after an averaging of 29.5 s, corresponding to 30 successive acquisitions. Each acquisition is composed of 30 successive frames of the interferometric signal, with 32.8 ms duration per frame. Both interferometers are synchronized to extract the observables at the same time.

The calibration step of the interferometers was mandatory to get reliable experimental results. This step is done on a point-like star, giving contrast and phase closure terms theoretically equal to 1 and 0, respectively. This way, we correct the experimental bias up to get $C_{ii} = 1$ and $\phi = 0$.

The contrast and the phase closure are measured for four photoncounting levels: 1 063 ph frame⁻¹, 300 ph frame⁻¹, 71 ph frame⁻¹ and 22 ph frame⁻¹ (i.e. 32 409 ph s⁻¹, 9 146 ph s⁻¹, 2 165 ph s⁻¹ and 671 ph s⁻¹, respectively). In addition, for each photon flux level, 164 dark counts per second must be taken into account. The lowest level investigated is related to the dark counts of our visible detector. Indeed, a level of 22 ph frame⁻¹ corresponds to around 7.3 ph frame⁻¹ (223 ph s⁻¹) for each interferometric arm. This photon counting level is in the same order of magnitude as the five dark counts per frame (i.e. SNR \approx 1) for each arm.

We have checked the influence of the pump source on the photoncounting events. Without any signal source and only the pump source propagating in the PPLN-waveguides, the number of photon per frame does not change. This demonstrates that no additional non-linear noise is detected and the flux level limitation is only related to the dark counts of the detector.

The contrasts (Fig. 8) and the phase closure (Fig. 9) measurements achieved in photon counting mode are plotted as a function of the contrast and phase closure measurements achieved in high flux regime with the reference infrared interferometer. A perfect operation of the upconversion interferometer would lead to an experimental curve aligned with the y = x one. The red crosses plot the raw signal and the black crosses the corrected signal using equations (6) and (8). For an easier representation of the results, we plotted the error bar of the lowest photon counting flux level. In this case, the error bars are in the range 4×10^{-3} and 11 mrad for the contrasts and the phase closure measurements, respectively. These very low dispersions of contrasts and phase closure measurements demonstrate the stability of our upconversion interferometer.

When the photon-counting signal level decreases, the uncorrected contrasts give biased information while the effect of Wirnitzer bias corrections applied to the contrast measurements is obvious. As can be seen, even for the lowest optical flux level (22 ph frame⁻¹), the corrected contrasts obtained with the upconversion



Figure 8. The contrasts measured in photon counting mode are plotted as a function of the contrasts measured for high flux levels. The red crosses plot the uncorrected signals and the black crosses the corrected contrasts. Error bars, not plotted here, are in the range of 3.87×10^{-3} . Five dark counts due to the detector must be added to each photon counting level.



Figure 9. The phase closure measured in photon counting mode is plotted as a function of the contrasts measured for high flux levels. The red crosses plot the uncorrected signals and the black crosses the corrected phase closures. Error bars, not plotted here, are in the range 11.2 mrad. Five dark counts due to the detector must be added to each photon counting level.

interferometer are in perfect agreement with the reference interferometer results (data aligned with the y = x curve).

Let us focus on the phase closure acquisition. We can see in Fig. 10 that lower values of phase closure are in agreement with the upconversion and reference interferometers. As previously de-



Figure 10. Experimental (crosses), simulation (dots) of phase closure terms and triple product (dash line) are plotted versus the phase closure terms measured in the high flux level.

scribed (Longueteau et al. 2003), when the number of photon becomes very low, the standard deviation of the phase closure measurements increases and the correction is altered. To corroborate and extend Longueteau's study, we notice that when the value of the triple product ($C_{12}C_{23}C_{31}$) is low, the phase closure correction fails and the phase closure term tends to 0. As can be seen in Fig. 10, plotting ours simulated (based on Wirnitzer bias corrections formulas) and our experimental results, the high triple product values give rise to small phase closure deviations whereas the small triple product values are related to high phase closure deviation. This suggests that in our apparatus reliable acquisitions of the phase closure terms at low flux levels requires an additional correction which depends on the triple product values. The nature of the correction remains to be determined.

According to the experimental results obtained with our upconversion interferometer configuration, the next paragraph presents the m_H limiting magnitude in H band for several experimental configurations of a three-arm interferometer.

5 LIMITING MAGNITUDE ESTIMATION OF AN UPCONVERSION INTERFEROMETER CONFIGURATION

The following part is a preliminary study to estimate the limiting magnitude of an upconversion interferometer based on our experimental results. We estimate the limiting magnitude in *H* band for several configurations of a three-telescope upconversion interferometer (see Fig. 11). We used a 223 ph s⁻¹ flux level reference for each interferometric arm. This flux level corresponds to the lowest level used in our upconversion interferometer.

The magnitude estimation strongly depends on the optical properties of the components to be inserted in the interferometer. Since our test bench is a demonstrator, its components were not fully optimized. Nonetheless, we compute several magnitudes based on our test bench properties and for two upgraded configurations of the upconversion interferometer (using commercially available components). For these configurations, the limiting magnitude is given for several mirror size. These estimations are based on an upconversion interferometer configuration using spatial filtering (spatially singlemode waveguides) and polarization maintaining components.

First, let us recall the expression of the magnitude m_H

$$n_H = -2.5 \log\left(\frac{F}{F^0}\right),\tag{19}$$

where $F^0 = 1.21 \times 10^{-13} \text{ W}\mu\text{m}^{-1}\text{cm}^{-2}$ is the reference flux level of Vega in *H* band centred at 1.62 µm and *F* the one for the observed star.

Equation (19) can be written as

ĸ

r

$$n_H = -2.5 \log\left(\frac{\Phi}{\Phi^0}\right),\tag{20}$$

where Φ and Φ^0 are the observed and reference intensity levels, respectively (given in watt). The computation of Φ^0 is given by

$$\Phi^0 = S_{\rm T} F^0 \Delta \lambda \tag{21}$$

where $S_{\rm T}$ is the collecting surface of the telescope and $\Delta\lambda$ the converted infrared spectral bandwidth equal to the spectral acceptance of the non-linear process. The estimation of Φ^0 will be performed for $\Delta\lambda = 0.3$ nm and $\Delta\lambda = 3$ nm. This last figure is related to a future configuration where wide-band frequency conversion benches would be used (in development in our laboratory).



Figure 11. A three-arm upconversion interferometer configuration for limiting magnitude estimation.

 Φ is the estimated minimum intensity that must be collected by one telescope. Its expression is given by

$$\Phi = \frac{\Phi_{\text{upconv}}}{T_{\text{inj}}T_{\text{mux}}T_{\text{SFG}}T_{dl}T_{\text{coupler}}\eta_{\text{detection}}}$$
(22)

where Φ_{upconv} is the minimum flux level of the converted signal equal to $N_{\rm conv} \times hv_{\rm c}$, with h the Planck constant and $N_{\rm conv} = 223 \,{\rm ph}\,{\rm s}^{-1}$ for one interferometric arm. T_{inj} is the coupling efficiency from a telescope to the single-mode optical waveguide of our PPLN (Shaklan & Roddier 1988). We set the T_{inj} parameter assuming a Strehl ratio of 0.6 and a coupling efficiency in a single-mode waveguide of 42 per cent taking into account a relative central obstruction (Coudé du Foresto et al. 1996b). T_{mux} takes the optical coupling of the pump source and the infrared starlight in the multiplexer output into account. T_{SFG} is the transmission efficiency of the whole frequency conversion bench. Notice that this parameter takes the frequency conversion efficiency of the PPLN and the optical losses through the filtering stage into account. T_{dl} characterizes the optical transmission of the DL. We keep the test bench value due to the fact that DL transmission of current interferometers is difficult to find. T_{coupler} is the global transmission of the optical recombination stage of the upconversion interferometer. T_{pol} is the polarization factor related to the use of polarization maintaining components. $\eta_{detection}$ is the quantum efficiency of the Si photon-counting detector.

We evaluated three configurations. The first one, called 'A', uses the data corresponding to the current configuration presented in this paper. The second one, 'B', is a configuration using the best components available in the market with lower optical losses and with a higher frequency conversion efficiency as currently developed in our laboratory. In this 'B' configuration, the infrared spectral width remains equal to 0.3 nm yielding in a 5000 spectral resolution of the interferometer in *H* band. The last one, 'C' configuration, is an upgraded version of the upconversion interferometer using wide-band frequency conversion benches. The infrared spectral width would be equal to 3 nm (i.e. 500 spectral resolution). For this purpose, a wide-band frequency conversion process is under development in **Table 1.** Transmission values for the A, B and C configurations of the upconversion interferometer. 'A' configuration corresponds to the current parameters of the upconversion interferometer, 'B' configuration uses the best components available in the market and higher frequency conversion efficiency and 'C' configuration uses wide-band frequency conversion benches. 'A' and 'B' configurations have a 5000 spectral resolution and 'C' a 500 spectral resolution. $\eta_{detection}$ is the quantum efficiency of the detector and Φ the optical flux level of the observed star in *H* band.

	А	В	С
T _{inj}	0.25	0.25	0.25
T _{mux}	0.5	0.74	0.74
$T_{\rm SFG}$	0.014	0.08	0.2
$T_{\rm dl}$	0.25	0.25	0.25
T _{coupler}	0.045	0.1	0.1
$T_{\rm pol}$	0.5	0.5	0.5
$\eta_{\text{detection}}$	0.6	0.8	0.8
$\Phi[fW]$	12.0×10^{3}	475.4	190.2

our laboratory. Table 1 gives the values of the parameters described above for the three configurations.

The corresponding limiting magnitude has been reported in Table 2 for the three configurations. These magnitude estimations are performed in H band centred around 1542 nm with a spectral bandwidth of 0.3 and 3 nm. These results show an interesting way to achieve spectral analysis using the frequency conversion process.

Note that the signal-to-noise ratio could be improved by long time exposure measurements. In our experimental configuration, the contrast and phase closure measurements are achieved in about 29.5 s. This way, higher limiting magnitude could be reached and

 Table 2. Limiting magnitude estimated for a 1-m, 2-m and 8-m class mirror in a three-telescope array configuration.

	1-m class	2-m class	8-m class
А	-4.1	-2.6	0.4
В	-0.6	0.9	3.9
С	2.9	4.4	7.4

so fainter objects observed. Moreover, in the current experimental set-up, the main limitation is due to the dark counts of the detector, which is equal to 164 Hz. Notice that commercially available detectors currently exhibit a 10 Hz dark counts rate. Using these kinds of detectors will allow us to increase the limiting magnitude of our upconversion interferometer.

6 CONCLUSION AND DISCUSSION

We successfully proved that our upconversion interferometer is reliable for the acquisition of contrasts and phase closures in photoncounting regime. We took care about the stability of the interferometric signal over the time. For this purpose, we used polarization maintaining and spatially single-mode optical components to obtain steady and high fringe contrasts. A laboratory star simulator lights a three-telescope array that feeds two interferometers working in parallel. The first one, operating at the same wavelength as the laboratory star, is used as a reference interferometer. With this instrument, the interferometric signal is detected in high flux level. The second one is the upconversion interferometer under test, with a frequency conversion bench placed on each interferometric arm. The observable is extracted from the photon noise using the Wirnitzer bias estimators.

This paper shows the perfect agreement between theoretical and experimental acquisitions of the contrast terms for both interferometers. For the phase term, a bias on the phase closure terms, due to the low level of the triple product, must be taken into account to get reliable data. Nonetheless, for high values of the triple product, the theoretical and experimental acquisition of the phase closure are in very good agreement. The current limitation of our upconversion interferometer is mainly due to the dark counts of the photon counting detector. Despite the fact that our test bench is not optimized, we showed that interesting magnitude could be reached on two high spectral resolutions of 500 and 5000 in H band. Notice that these results can be extrapolated to other wavelength domains and the possibility to reach unexplored optical windows is very promising. It will be possible to use the idea of upconversion interferometer on optical windows such as H band and later the L or the N band. Judiciously choosing the wavelength of the converted signal would allow the use of detectors with a very low level of dark counts, high quantum efficiency, continuous wavelength application, fast response, cost-effective and without need of complex cryogenic temperature stabilization of all the components (if frequency conversion is made right after the primary mirror). The use of frequency conversion benches makes the interferometer versatile; one just has to change the non-linear crystal to have access to other spectral windows, the rest of the device remaining unchanged. This is a very attractive alternative to the classical way that uses a dedicated experimental chain for each astronomical spectral window.

ACKNOWLEDGEMENTS

This work has been financially supported by the Centre National d'Études Spatiales (CNES) and by l'Institut National des Sciences de L'Univers (INSU). We are grateful to A. Dexet for his suggestions for regarding all the specific mechanical components.

REFERENCES

- Baron F. et al., 2012, AJ, 752, 20
- Berger J.-P. et al., 2003, Proc. SPIE, 4838, 1099
- Bonneau D., Chesneau O., Mourard D., Stee P., 2010, preprint (arXiv:1001.1920v1)
- Born M., Wolf E., 1980, Principles of Optics, 6th edn, Pergamon Press, Oxford
- Boyd R. W., 2008, Nonlinear Optics, 3rd edn. USA Academic Press, p. 69
- Brustlein S., Del Rio L., Tonello A., Delage L., Reynaud F., Herrmann H., Sohler W., 2008, Phys. Rev. Lett., 100, 153903.1
- Ceus D., Tonello A., Grossard L., Delage L., Reynaud F., Herrmann H., Sohler W., 2011, Opt. Express, 19, 8616
- Ceus D. et al., 2012, MNRAS, 427, L95
- Coudé du Foresto V., 1997, C. R. Acad. Sci. Paris, Série II b, 325, 177
- Coudé du Foresto V., Perrin G., Mariotti J.-M., Lacasse M., Traub W., 1996a, in Kern P., Malbet F., eds. Proc. AstroFib'96, Integrated Optics for Astronomical Interferometry. Bastianelli-Guirimand, Grenoble, p. 115
- Coudé du Foresto V., Faucherre M., Hubin N., Gitton P., 1996b, A&AS, 145, 305
- Delage L., Reynaud F., 2000, J. Opt. A. : Pure Appl. Opt., 2, 1
- Delage L., Reynaud F., Lannes A., 2000, Appl. Opt., 39, 6406
- Froehly C., 1981, in Ulrick M. H., Kjar K., eds, Proc. ESO Conf. on 'Scientific Importance of High Angular Resolution at Infrared and Optical Wavelengths'. ESO, Garching, p. 285
- Jennison R. C., 1958, R. Astron. Soc., 3, 276
- Le Bouquin J.-B. et al., 2011, A&A, 535, A67
- Longueteau E., Delage L., Reynaud F., 2003, Opt. Commun., 217, 75
- Louisell W. H., Yariv A., Siegman A. E., 1961, Phys. Rev., 124, 1646
- Nikogosyan D. N., 2005, Nonlinear Optical Crystal. Springer, New York, p. 427
- Olivier S. et al., 2007, Appl. Opt., 46, 834
- Petrov R. G. et al., 2007, A&A, 464, 1
- Renard S., Thiébaut E., Malbet F., 2011, A&A, 533, A64
- Shaklan S., Roddier F., 1988, Appl. Opt., 27, 2334
- Smith H. A., Townes C. H., 1969, in Polarization, Matière et Rayonnement. Presses Universitaires de France, Paris, p. 467
- Wirnitzer B., 1985, J. Opt. Soc. Am. A, 2, 14

This paper has been typeset from a TEX/LATEX file prepared by the author.