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Prospects of Optical Heterodyne Detection for Astronomy and One Photon Interferometry

E. le Coarer[1], A. Chalabaev[1], & G. Duvert[1]

[1] *UJF-Grenoble 1 / CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble, UMR 5274, 38041, Grenoble, France*

Abstract. Within the framework of spatial and spectral interferometry, new prospects for optical heterodyne detection in astronomy are sketched in order to take into account the emergence in recent years of frequency comb lasers, absolute time networks and dramatic progress in the field of light detection. We also describe a laboratory experiment of one photon spatial interferometry which indicates a new way to detect photons one by one by using heterodyne technic and to improve significantly the signal to noise ratio.

1. Introduction

The heterodyne detection for stellar interferometry in the infrared has been promoted in 1970's (see e.g. Johnson, Betz and Townes, 1977; and review by Gay, 2013 in this volume). The main motivation of the heterodyning is the hope that the signal at the resulting reduced frequency is more easy to be handled than the infrared or optical light and hence a larger baselines are possible. However, the S/N figure of direct interferometry is in general higher. The ratio of S/N of direct and heterodyne detections can be evaluated by the following relation $\frac{1300}{T_D}\sqrt{\frac{\Delta\nu_D}{\Delta\nu_H}}$, where T_D is the noise temperature of the direct detection, roughly $300^\circ K$, $\Delta\nu_D$ and $\Delta\nu_H \approx 6\cdot 10^9 Hz$ are the bandwidths of the direct and heterodyne detections respectively (Towns and Wishnow, 2008). The interest of the heterodyne method was hence limited to a small number of special astronomical cases. Nowadays, all stellar interferometers are direct except ISI (for its latest description see Wishnow et al., 2010).

2. New Numbers

So far, the heterodyne detection was considered with the use of one laser. Today, one can use the laser frequency combs (Udem, Holzwarth and Haensch, 2002; Steinmetz et al, 2008). Such lasers provides several thousands lines, each of them can be separated by a R=40000 spectrometer. Individual lines may be used as local oscillator. An optical fiber carrying the signal coming from sky and another one carrying the laser signal are placed together in the slit environment in the spectral dispersion direction with a little shift in order to insure the up or down shifting according to the local oscillator. The mixing of light is then operated by the detector itself which also amplifies both signals. Each pixel of the detector is sensitive to the beating terms and acts as a heterodyne channel. A basic approach permits us to gain on the sensitivity as the square root of number of pixel used.

The stability of the frequencies can be insured by high precision metrology network Refimev+ (Refimev project, 2013). A 10^{-17} precision and stability can be foreseen in a local telescope network fed by black fibers systems, allowing to date every signal detection at each telescope.

The bandwidth can be as high as several $10^{12} Hz$ using MCT APD detectors acting either as photon counting devices or analog devices. Such devices are able to multiply a photoevents without adding spurious noise (Rothman 2008).

The whole measure of the light coherence can be considered in a more straight way as shows the experiment described below.

3. Experiment of spatial interferometry down to one photon

The major renewal of heterodyne detection could be made by the detection of photon itself. Can the mixing of a continuous very stable laser line and a single photon be detected as a single heterodyne event? The noise generated by laser as a level of $\sqrt(N)$, N number of photon in time units. The signal provided by the mixing of one photon and this laser gives a $2\sqrt(N)$ signal level. With this assertion we estimate that it is possible to separate during time an individual heterodyne events in order to record this signal only during few nanoseconds avoiding to record noise during time separating two successive events as it is done in simple photon counting. Because we have not yet demonstrate this detection scheme, we would present here an analogy based on Young interferometry. In this simple set-up of the Young experiment, the laser light is split on two beams by a Y-junction. The light emitted by the fiber end holes gives rise to the interference pattern directly on the detector. The nice system of rings comes from an importune interference on the cryostat window. The Young fringes are the vertical lines.

The high speed of the OCCAM2 detector, 1300 frames/s, makes possible to explore what happens to the Young interference when there are less and less photons per frame coming from one of the the two arms keeping the same flux in the other arm. The Fig. 1 shows the interference in the Fourier space of a very dissymmetric setup. The image of the power spectrum exhibits the expected pics of the visibility on the both side of the central maximum.

We can write the well known relation for the intensity of interference:

$$I = I_{source} + I_{laser} + 2\sqrt{I_{source} I_{laser}} \cdot cos(\omega_{laser} - \omega_{source})t \tag{1}$$

where I_{source} is the light intensity in the attenuated arm of our set-up. We can also write this relation expressing intensities in units of the energy of 1 photon. For $I_{source} = 1$ in this units, we get:

$$I = 1 + I_{laser} + 2\sqrt{I_{laser}} \cdot cos(\omega_{laser} - \omega_{source})t \tag{2}$$

The noise is then $\sqrt{I_{laser}}$ and the intensity of the beat term is $2\sqrt{I_{laser}}$.

The amplitude of the central peak of this average of 10000 frames is 223800 detections/frame, that of the secondary peak is 1300 detections/frame. The amplitude of the visibility is $2 \cdot 10^{-3}$.

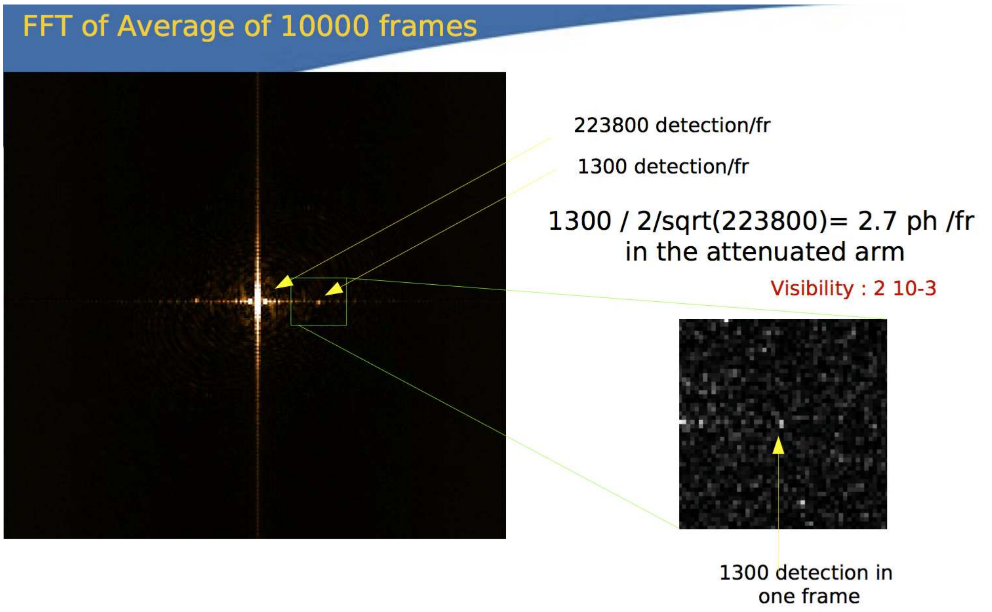
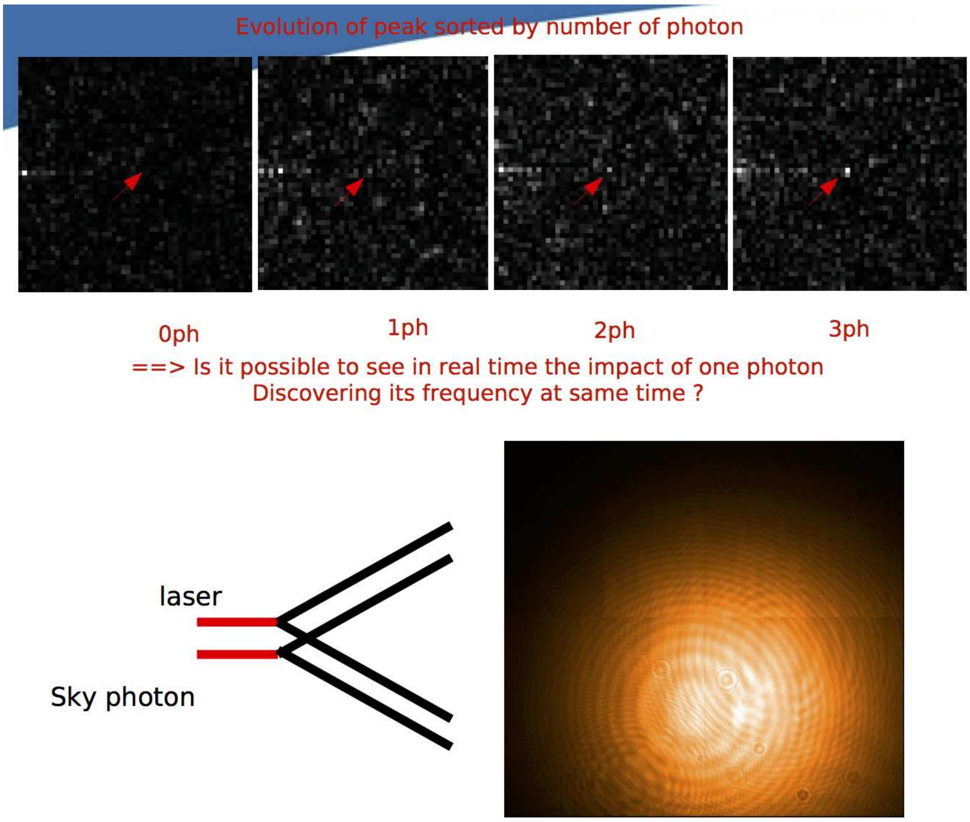


Figure 1.: *The power spectrum*

Given that $I_{laser} >> I_{source}$, and assuming that the detector quantum efficiency is 1, we get $I_{source} = 1300/(2\sqrt{223800}) \approx 3$ photoevents/frame. Fig. 2, we show the evolution of detections on the secondary peak as is they were solely due to the fluctuations of the number of photons in the attenuated arm: 0 photons, 1 photon, and so on. Of course, the amplitude of fluctuations of the laser contribution about 470 photoevents must also be taken into account, however this does not affect the following conclusion: We can detect 1300 photoevents/frame on the secondary peak even if there are only 3 photons in average coming from the source. We can say that the interference is not the combinatory of photons thought as solid particles and counted one by one but a phenomenon implying quanta of electro-magnetic field. One can count 1300 photoevents/frame due to the interference of a laser light with 1, 2 or 3 photon intensity source, and this is encouraging for the prospects of the heterodyne stellar interferometry in the optical and infrared.

4. Conclusions

So far, the heterodyne technic at near infrared and visible light domains has been considered as a dead end because of the lack of photon of astronomical sources at a GHz rate. In this communication, we described a new way to use heterodyning, namely, the detection of single photons mixed with high stabilized laser. If we are able to isolate and record the effect of individual photon, the signal to noise of heterodyne interferometry should compete with direct interferometry.



Evolution of peak sorted by number of photon

==> Is it possible to see in real time the impact of one photon
Discovering its frequency at same time ?

Figure 2.: *Photoevents*

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