The ALOHA project: joint use of fiber and nonlinear optics for high resolution mid-infrared imaging

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The Astronomical Light Optical Hybrid Analysis (ALOHA) project investigates a new method for high resolution imaging in mid-infrared astronomy. We propose to shift the astronomical spectrum to be investigated from the mid-infrared (MIR) to the near-infrared (NIR) where the instrumental chain can be operated in a technologically-mature wavelength domain and where nearly ideal photon detection technology is available.

The frequency shift is realised by an "up-conversion stage" based on sum frequency generation (SFG), where the astronomical science signal at frequency ν_s is mixed with an intense and highly coherent pump wave at frequency ν_p to generate a converted wave at frequency $\nu_c = \nu_s + \nu_p$. This second-order nonlinear conversion is obtained in Periodically Poled Lithium Niobate (PPLN) waveguides, which feature a high non-linear coefficient, and allow a long interaction length. The conversion efficiency depends however on the phase matching condition between the interacting waves, which states that the locally generated waves at ν_c have to interact constructively in the non-linear waveguide during propagation. This results in a spectral selectivity described in [1].

This non-linear process is particularly interesting for high resolution imaging based on spatial coherence analysis. Firstly, the coherence properties of the signal waves are preserved during the up-conversion process. The phase of the astronomical science signal is merely transferred to the converted wave. This requires the use of a pump laser with a great coherence length. Secondly, SFG process is known to be intrinsically noiseless [2], as the science signal and pump waves must be simultaneously present to generate the converted field.

There are several advantages of using such a frequency conversion, especially from MIR to NIR or visible wavelengths :

- this makes it possible to use spatially single-mode and polarisation maintaining components such as optical fibers and integrated optical combiners, which are easy to handle and have very low optical losses,
- efficient photon counter detectors with high quantum efficency, low noise and room temperature operation are available in the NIR.
- therefore, assuming that the frequency conversion takes place right after the telescopes, no complex cooling system is required over the entire instrument.

Figure 1 shows the ALOHA concept compared to classical methods. The most common configuration initially proposed by Fizeau is an interferometer where the optical signals are mixed before detection

(Fig. 1.a). This configuration has been firstly experimentally demonstrated by Michelson on the Hooker telescope at the Mount Wilson Observatory (CA, USA), and then extended to the use of several separated telescopes by A. Labeyrie. Today, current hectometric telescope arrays such as the VLTI in Chile and the CHARA Array at Mount Wilson are based on this architecture.

In a very similar way, the spatial coherence can be analyzed after an optical to electric conversion in appropriate photodetectors (IR detectors) followed by a subsequent electronic cross correlation. This can either be done by direct detection (Fig. 1.c) as proposed by Brown and Twiss or by heterodyne detection (Fig. 1.b) as experimented by Townes. In this latter case, the optical signals are mixed with a local optical oscillator which strongly improves the sensitivity. However, in both cases, highly sensitive ultrafast photodetectors are required, which are not available for the mid-infrared spectral domain.

The ALOHA concept (Fig. 1.d) lies between the heterodyne intensity interferometer proposed by Townes and the classical optical interferometer. The main difference lies in the ability to cross-correlate the optical waveform after the upconversion steps, rather than the electrical signals after detection.

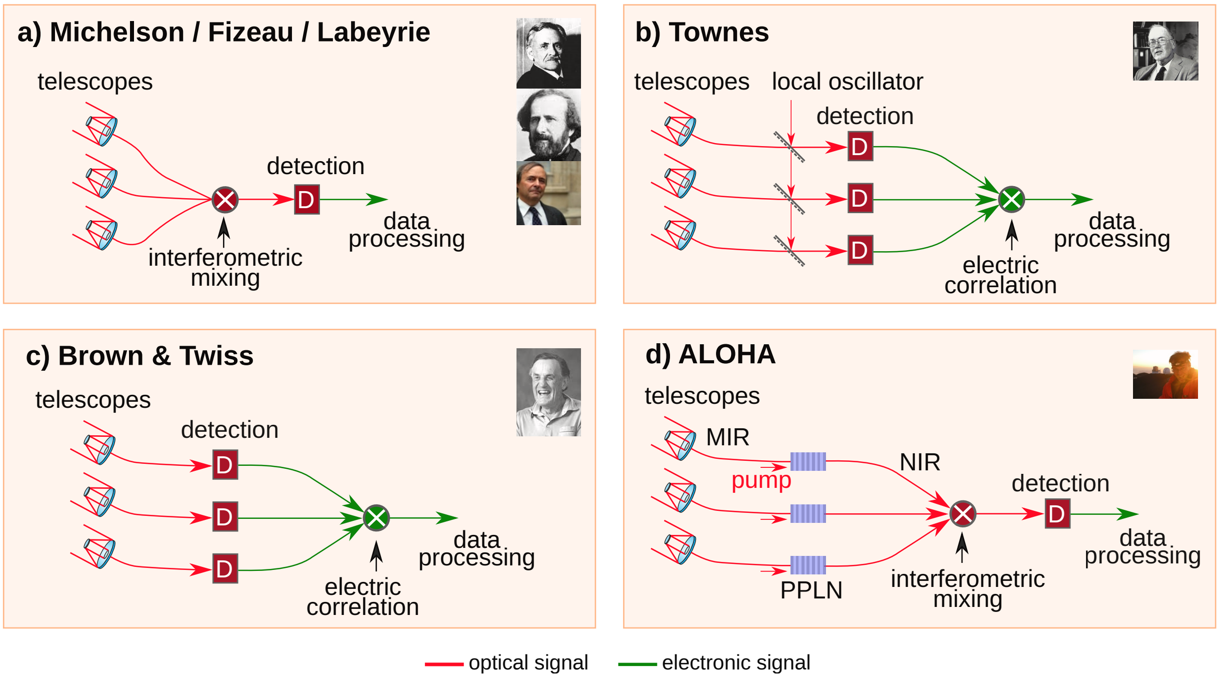

FIGURE 1 : Comparative presentation of the three classic configurations and the ALOHA concept (bottom right). Top left : the most common method uses the field correlation. The two intensity correlation measurements (direct and heterodyne) are shown top right and bottom left).

The first proof-of-principle was demonstrated in 2008 in the H-band using a DFB laser as a source signal [3]. After laboratory demonstrations in the photon-counting regime with a blackbody source [4], the experiment was modified and tested at the CHARA Array in 2015. On-sky fringes were obtained using the S1 (South 1) and S2 (South 2) telescopes, with H-band sources up-converted to the visible spectral domain [5] with a limiting magnitude $H_{mag} = 3.0$. These positive results in the H-band convinced us to develop an ALOHA prototype in the L-band. In a first study, interference fringes were first obtained in the laboratory at 3.39 µm with an attenuated monochromatic laser as the source signal[6]. The up-conversion process was then validated on-sky in the L band with one telescope of the C2PU facility (Observatoire de la Côte d'Azur, Calern site, France ; `https://www.oca.eu/fr/c2pu-accueil`). Sensitivity tests were conducted in the photon counting regime, reaching a $L_{mag} = 2.8$ limiting magnitude in the L band [7]. In 2020, an up-conversion interferometer using a blackbody source and a wavefront division in the L band at 3.4 µm was demonstrated in the laboratory [8].

We are now focused on the implementation and first tests of the ALOHA prototype in the L band at the CHARA Array. Fig. 2 shows a schematic view of the ALOHA project implemented at CHARA. The 3.4 µm light is collected by the two telescopes S1 and S2. The collected light is then up-converted to 810 nm thanks to PPLN waveguides operating at room temperature, and a pump laser beam at 1064 nm propagating into 50 m polarisation maintaining (PM) fibres. The converted light is then injected into 240 m PM fibres towards the recombining laboratory and propagates through the CHARA free space delay lines. After the interferometric mixing, the two interference signals are spectrally filtered and detected by photon counters.

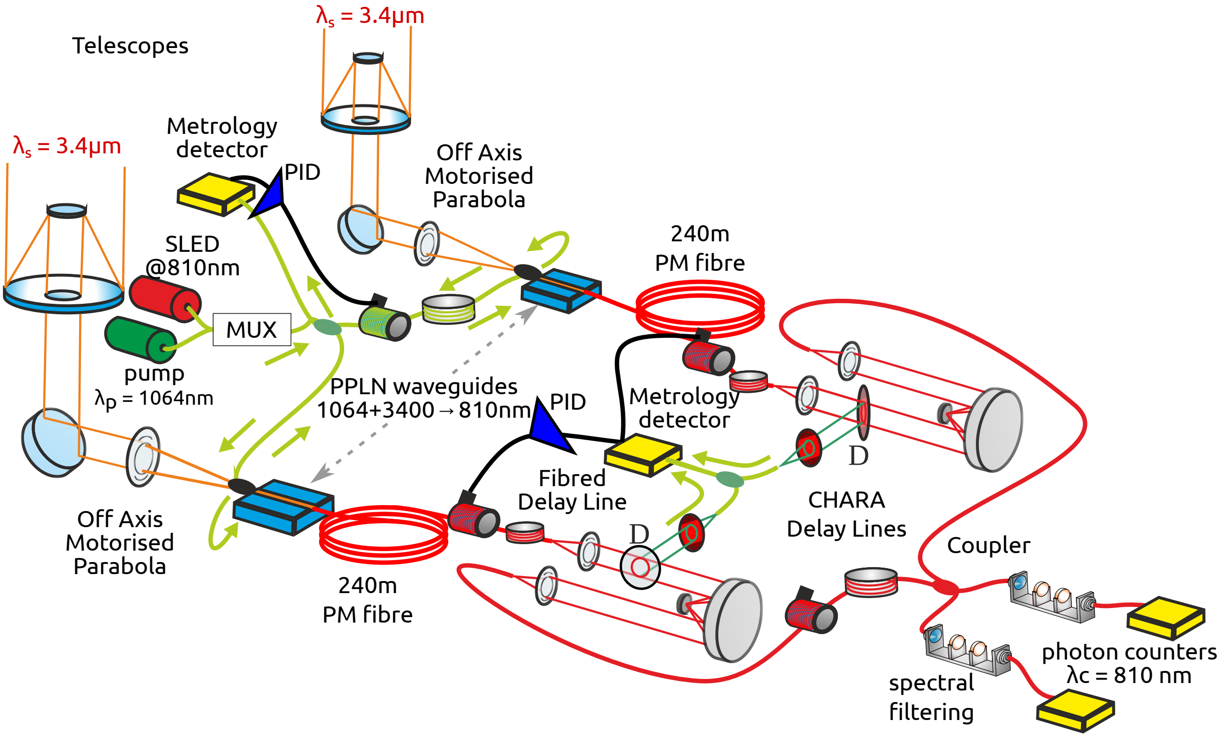

FIGURE 2 : ALOHA implementation at CHARA : the light collected at 3.4 µm is converted at 810 nm thanks to a 1064 nm pump laser and nonlinear PPLN waveguides. The pump light propagates through 50 m long PM fibres. The converted light then passes into 240 m PM fibres towards the CHARA free space delay lines. After interferometric recombination, the interferometric signal is detected in the photon counting regime. Two cascaded servo control systems are used to stabilise the OPD of the pump and converted signal fibres. SLED : Superluminescent Diode, PID : Proportional–Integral–Derivative controller, MUX : Multiplexer.

After initial tests of stabilisation of an outdoor fiber link interferometer [9], we have implemented in 2022 the servo control systems of the pump and converted signal fibres that stabilise the optical path difference (OPD) between the two arms of the interferometer of ALOHA. Using optical fibre modulators, fibre delay lines, and the pump laser at 1064 nm as a metrology source, the OPD has been succesfully stabilised within 3 nm RMS over a 3000 s record[10]. Using an internal source at 810 nm (SLED), the signal-to-noise ratio of the fringe modulation peak was enhanced by a factor better than two when the servo control was switched on. Then, we recorded on-sky fringes at 810 nm (without the nonlinear up-conversion stage) on the star Vega during two consecutive nights, and showed the contribution of OPD stabilization on the contrast of interference fringes and on the signal-to-noise ratio.

This study is a seminal work towards very long base fibre linked telescope arrays and allows to scale the perturbative environment of an outdoor fibre link. This type of servo control system is one of the key technologies necessary for the deployment of very long base telescope arrays like the future CHARA kilometric infrared interferometer [11].

On future missions, we plan to test the complete ALOHA interferometer at CHARA, integrating the frequency up-conversion stages of mid-infrared light at 3.4 µm.

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