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ORIGINAL ARTICLE

# ALOHA—Astronomical Light Optical Hybrid Analysis

## From experimental demonstrations to a MIR instrument proposal

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**Abstract** This paper gives an overview of the Astronomical Light Optical Hybrid Analysis (ALOHA) project dedicated to investigate a new method for high resolution imaging in mid infrared astronomy. This proposal aims to use a non-linear frequency conversion process to shift the thermal infrared radiation to a shorter wavelength domain compatible with proven technology such as guided optics and detectors. After a description of the principle, we summarise the evolution of our study from the high flux seminal experiments to the latest results in the photon counting regime.

**Keywords** High angular resolution · Interferometry · Optical fibre · Non-linear optics · Aperture synthesis · Sum-frequency generation

## 1 Context

Over the last decades, a greatly improved knowledge of the Universe and, more generally, of astrophysical sources has been achieved by means of huge telescope arrays. These very large instruments are able to provide the best sensitivity/spatial resolution trade-off to observe astrophysical sources with a sharp analysis never reached before. To investigate the wide wavelength domain, a large variety of instruments

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have been designed and implemented. Even in this limited optical spectral domain, the usual way to propose an instrumental concept is to develop an experimental chain (including the collecting antenna, wave propagation, optical processing and detection) specifically dedicated to the spectral window to be investigated (see Fig. 1). For ground observation, these bands (J, H, K, etc.) are defined by the transparency of the atmospheric layer. Nonetheless, this method can lead to very complex designs and stringent manufacturing of the related optical components to be implemented in the instrument. It results in poorer performance for the current instruments dedicated to the mid and far infrared (MIR and FIR) than in the visible and near infrared.

With a completely opposite approach, we propose to use an instrumental chain operated in a technologically-mature wavelength domain and to shift the astronomical spectrum to be investigated into this propitious spectral window, where nearly ideal photon detection technology is available. This completely new approach allows us to propose a new generation of instruments able to address the problem of the mid and far infrared spectral domain, which is very informative for astrophysical studies (Active Galaxy Nucleus, Young Star Objects, exoplanets…).

The key point in this new concept is the possibility to convert the light from a far infrared wavelength to the visible or near infrared wavelength range through an "up-conversion stage" as shown in Fig. 2. For this purpose, it is possible to use sum frequency generation (SFG). This second order non-linear process allows us to merge the astronomical science signal at frequency $\nu_s$ with an intense and highly coherent pump wave at frequency $\nu_p$ in order to generate a converted wave at frequency $\nu_c = \nu_s + \nu_p$. Periodically Poled Lithium Niobate (PPLN) waveguides are very good candidates for SFG for their very high non-linear coefficient and field confinement, and long interacting length. The conversion efficiency depends however on the quasi-phase matching condition between the interacting waves, which states that the locally generated waves at $\nu_c$ have to interact constructively in the non-linear waveguide during propagation. This results in a spectral selectivity described in reference [2].

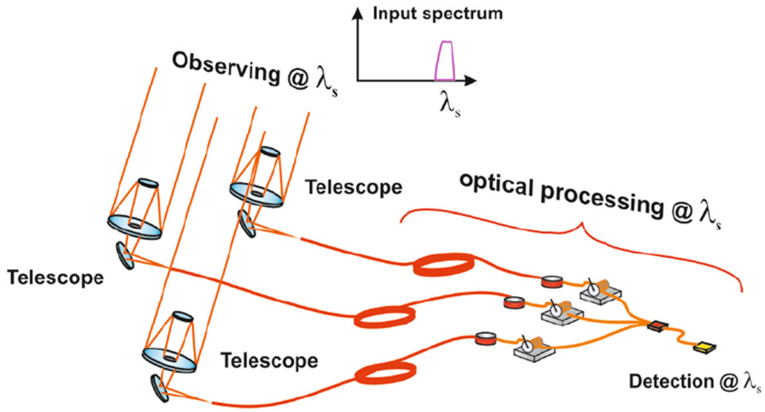


**Fig. 1** Classical telescope array configuration dedicated to high resolution imaging in astronomy. The interferences between the beams collected by the telescopes allow us to obtain high resolution spatial information on the astrophysical target

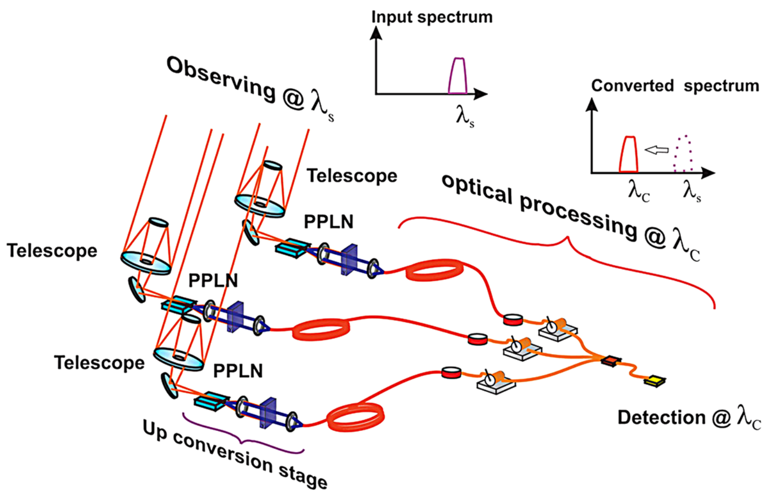


**Fig. 2** General scheme of our proposal. An up-conversion stage allows us to adapt the astronomical spectrum to a spectral window where a high performance interferometer can be implemented

This non-linear process is particularly interesting for high resolution imaging based on spatial coherence analysis for two main reasons. Firstly, the mutual coherence of the waves is preserved during the upconversion process because the phase of the astronomical science signal is 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 [10], 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 far and mid infrared to near infrared or visible wavelengths:

– the possibility of using spatially single-mode and polarisation maintaining components which are easy to handle and have very low optical losses (optical fibres and integrated optical combiners)
– the availability of efficient detectors (high quantum efficiency, low noise, room temperature operation)
– not to be compelled to use complex cooling systems over the entire instrument (assuming that the frequency conversion takes place right after the telescope focus).

### 1.1 The physical basis of this new concept

Why this new approach is different from the existing ones. Figure 3 shows a comparative summary of our proposal versus the classical previous ones.

The most commonly used configuration is an interferometer in which the optical signals are mixed before detection (Fig. 3a). This configuration has been proposed by Fizeau and firstly experimentally demonstrated by Michelson on the Hooker telescope at the Mount Wilson Observatory (CA, USA). In the middle of the 20th century,

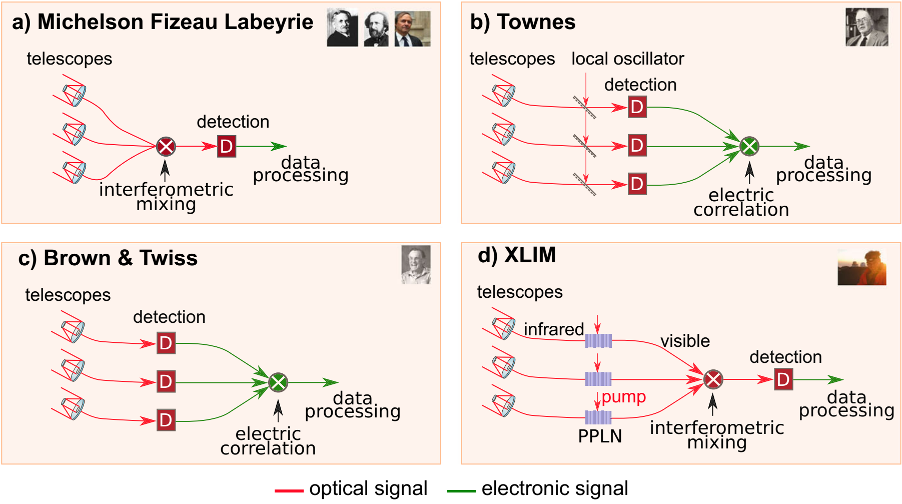


**Fig. 3** Comparative presentation of the three configurations previously investigated and our new concept (bottom right). Top left the most common method uses the field correlation. The two intensity correlation (direct and heterodyne) measurements are presented top right and bottom left)

A. Labeyrie has promoted the use of separated telescopes. Nowadays, it has resulted in the implementation of hectometric instruments such as the VLTI in Chile and the CHARA Array at Mount Wilson (USA/CA) that provide routinely astrophysical data in the near infrared spectral range.

In a very similar way, the spatial coherence can be analysed 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. 3c) as proposed by Brown and Twiss or by heterodyne detection (Fig. 3b) 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.

Our new concept (Fig. 3d) is not so far from a mix between the heterodyne intensity interferometer proposed by Townes and the one currently used on telescope arrays such as the VLTI or the CHARA Array. The main difference results from the possibility to make a cross-correlation of the optical wave after the up-conversion stages and not on the electric signals after detection. This is possible nowadays due to significant advances in the field of non-linear optics.

## 2 Feasibility and first experimental results

The following list reports the main results that make us confident to promote this proposal and on the possibility to succeed in a real astronomical context. All over the reported experiments, the observables to be recorded are related to the complex visibility of the fringes observed at the output of the interferometer: contrast and phase closure. In the following, the quality of their measurements will be used as a proof of the quality of the instrument under test.

- First high flux lab demonstration: fringe contrast preservation in an up-conversion interferometer [3].
- In lab phase closure preservation in an up-conversion interferometer at high flux level (Fig. 4).
- In lab operation of an up-conversion interferometer in the photon counting regime (narrow bandwidth, Ceus et al. [6]).
- Sensitivity tests at the Mauna Kea observatory: first stellar light conversion using a 20 cm C8 telescope [5].
- Operating an up-conversion interferometer with a blackbody source: in lab demonstration of the performances of the up-conversion interferometer on the most incoherent source fitting the real astronomical conditions [9].
- Large bandwidth conversion and spectral compression: when checking the nonlinear crystal properties, one of the main features is the spectral filtering performed by the sum frequency generation process. This spectral selectivity is related to the phase matching condition between the interacting waves through the nonlinear crystal. Notwithstanding the sensitivity requirement, this property can be turned as an advantage as performing a natural spectral analysis. We propose to use a multilaser pump emitting a spectral comb in order to address the various wavelengths of the broadband astronomic light. The first attempt has been conducted using PPLN waveguides at 1.55 $\mu$m with a pump comb at around 1.064 $\mu$m. First results have been obtained with two lines, demonstrating the basic principle. During this work we have observed a spectral compression on the converted signal [7].
- Photometric tests at the CHARA Array: in May 2014, we have performed a set of on-site photometric preliminary measurements using only one arm of the future instrument. During this mission, we have demonstrated the possibility to reach a Hmag = 2 with a 2600 spectral resolution. Several improvements have been

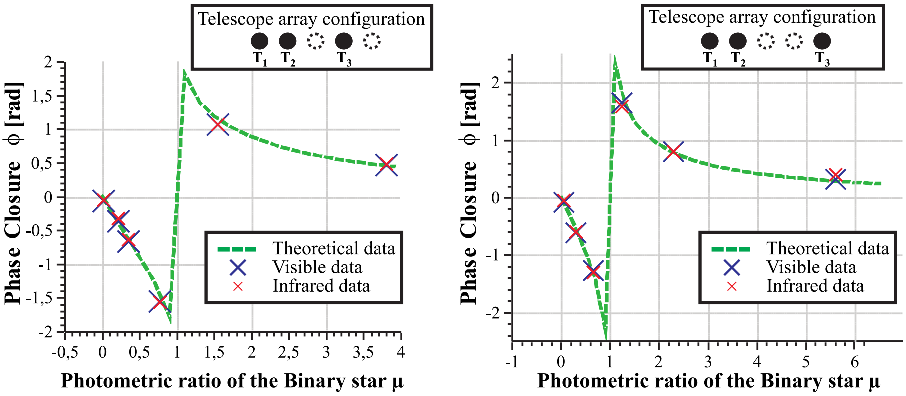


**Fig. 4** First demonstration of phase closure acquisition in a up-conversion interferometer [4]

achieved using the two interferometric outputs and some upgraded components [1].
- First on sky fringes at the CHARA Array: during the mission, in April 2015, we have tested the possibility to get fringes using a prototype of ALOHA dedicated to the H band. Despite the experimental environment due to the temporary installation of our set up out of the recombination laboratory, we have been able to get fringes observing real stars over a 0.6 nm spectral bandwidth (Fig. 5). The target magnitudes were between −0.6 and 3 and were spatially unresolved in the framework of this first on-sky demonstration (one and half night, Darré et al. 8).

The more efficient components being currently developed with Lithium Niobate crystals in the 1.55 $\mu$m wavelength domain, all the first preliminary investigations discussed above have been performed in the astronomical H band. We are now addressing longer wavelength spectral domains such as the L band, and in a near future the N band.

- First fringes at 3.39 $\mu$m have been obtained in laboratory in monochromatic and in high flux configuration using a MIR HeNe laser as a source, and PPLN crystals in the non-linear stages [13].
- In a second step, the laser source was attenuated to operate the experiment in the photon counting regime (Fig. 6, Szemendera et al. [14]).

These promising results allow us to plan the future developments of our instrument. The following paragraph proposes a roadmap paving the way of our study.

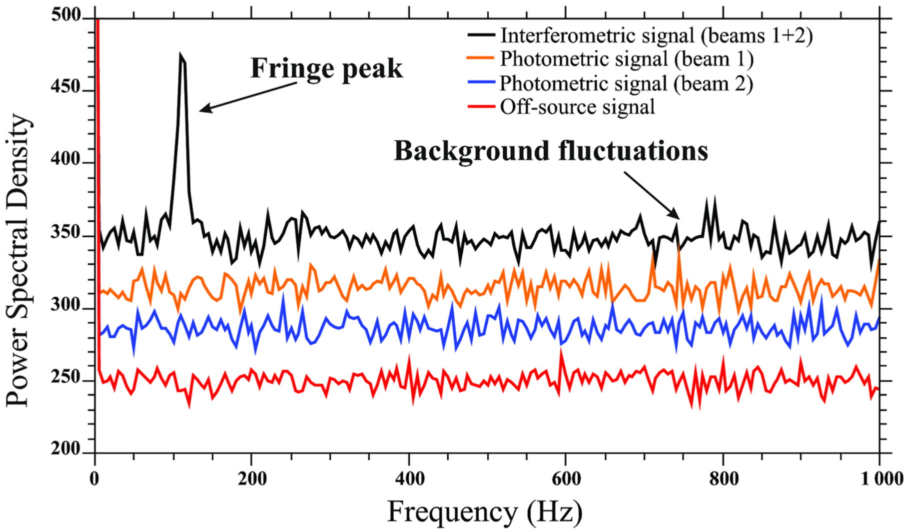


**Fig. 5** Experimental power spectral density (PSD) related to the $\alpha$ UMa interferogram. Black: interferometric configuration, blue and orange: photometric signals, red: interferometric configuration without signal source. From Darré et al. [8]

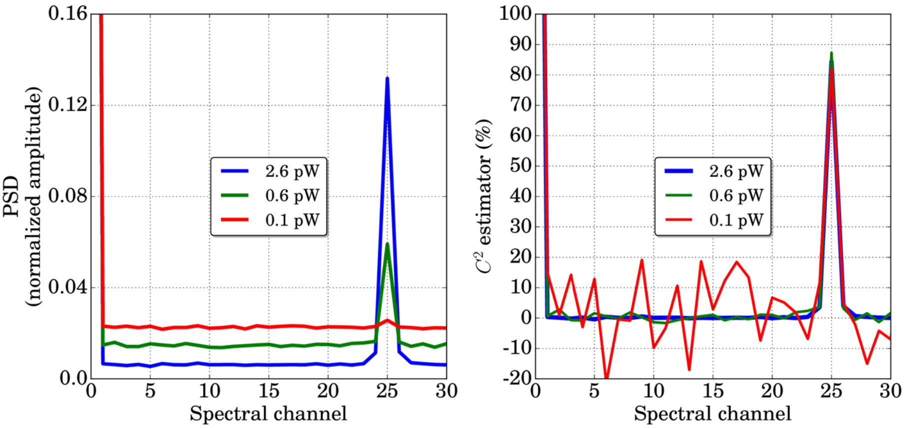


**Fig. 6** Left: normalised PSD obtained after integration over time for 3 different MIR input powers. Right: $C^2$ estimator as a function of the spectral channel derived from the normalised PSD and bias correction. From Szemendera et al. [14]

## 3 Outlook

In the coming five years we plan to develop our study in the following directions:

### 3.1 Further tests on the CHARA Array

Using the instrument developed in lab at 1.55 $\mu$m, we tested our concept on a real instrument in the astronomical H band as reported in Fig. 7. For this purpose, we are collaborating with the CHARA Array team. This instrument is a very good tool to validate new ideas, functions or data processing related to the new concept of

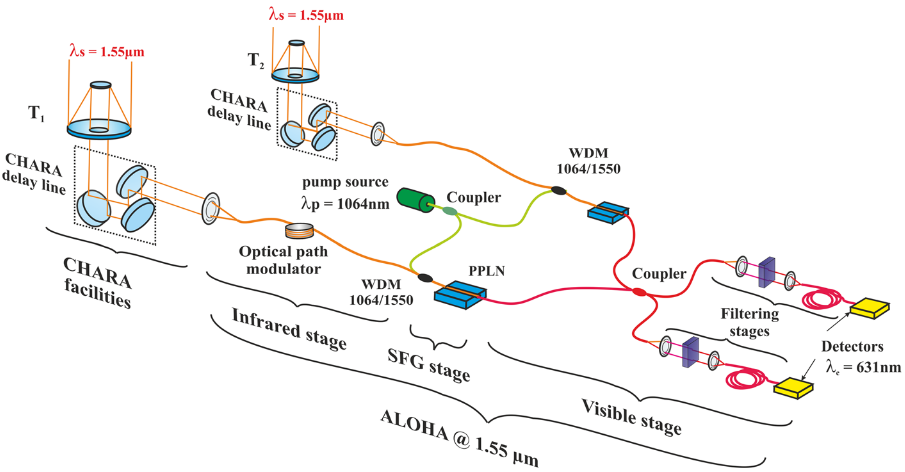


**Fig. 7** ALOHA implemented on the CHARA Array

SFG interferometer. We plan to improve the performances of the components in the H band, test a multichannel spectral configuration and the global architecture of the instrument to enhance its sensitivity. Notice that in the current status, our up-conversion interferometer is placed after the delay lines of the CHARA Array in order to minimise the complexity of the first on the sky demonstrations.

### 3.2 Towards MIR and FIR spectral domain

We are testing a two-arm interferometer using non-linear crystals provided in the framework of collaboration with FEMTO-ST (Besançon, France) for the MIR components (L band). The study has begun in laboratory with a high flux source to manage the full operation of the instrument and is going to be achieved with a black-body source down to the photon counting regime with very promising results. In parallel, sensitivity tests are planed on a 1m-class telescope (C2PU OCA France) in order to assess the limiting magnitude to be investigated with such an instrument.

The midterm prospect of this experiment plans to implement ALOHA L Band at the CHARA Array. The conversion will take place close to the telescope focus in order to minimise the impact of the instrument thermal background. The telescope to lab links will be achieved through single mode, polarisation maintaining fibres. Preliminary tests has demonstrated the possibility to reach an optical path stability compliant with the interferometric context. That could address the perspective of giant baselines using fibre linked telescope array.

### 3.3 Large spectral bandwidth and spectral analysis

To address larger spectra, we propose to use a multilaser pump emitting a spectral comb. Each line of the pump spectrum could select a spectral sample of the astronomical light. This configuration could be used either in a spectral analysis configuration (separation of the spectral channels) or in an integral mode (coherent sum of the spectral channels) by controlling the phases of the pumps. The first attempts have been conducted using non-linear waveguides operating at 1.55 $\mu$m with a pump comb around 1.064 $\mu$m. First results have been obtained with two lines demonstrating the basic principle. The spectral comb pump technique will be extended later to the MIR and FIR spectral domains.

### 3.4 Very long baseline MIR and FIR interferometers

The very low propagation losses in silica fibres allow us to propose a telescope array with a fibered link over very long baselines. To propose such kind of interferometers, two main difficulties must be overcome when working in the MIR or FIR domains:

- the first one deals with the spectral shift from the MIR and FIR to the silica fibre spectral window. This point will be fully answered by our up-conversion interferometer as long as efficient up-conversion is available.
- the second point concerns the possibility to design and implement an all guided delay line. Taking advantage of the spectral compression mentioned above, we

plan to propose this new delay line concept without any free space propagation. Our skills on fibre delay line manufacturing and fibre differential dispersion control will be very helpful during this work [11, 12].

## 4 Conclusion

The SFG interferometer is a very promising instrument for high resolution imaging in the MIR. The current strategy is to develop this kind of instrument in two main directions:

- a set of proof of principle experiments in order to valid the concept and to propose new functions,
- on sky tests to consider the astronomical requirement and demonstrate the potential of ALOHA.

Through a set of experiments developed at 1.55 $\mu$m (H band) we have demonstrated the principle of ALOHA thanks to the mature technology derived from telecommunication devices. However, in this spectral band, classical astronomical instruments are still developed and routinely operated. In this context, the MIR spectral domain is the final scope of development for our project. This breakthrough instrument could answer stringent constraints faced by the current MIR instruments. After in laboratory promising results in the L band, the next step will be focused on the sky investigation. Sensitivity tests in the L band are planned on 1 m-class telescopes (C2PU and CHARA). Combined with the characteristics of potential telescope array to be used (CHARA, VLTI) these results will give the inputs to define science cases to highlight the ALOHA capabilities.

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