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V8: AN 8 BEAM MID-INFRARED HETERODYNE INSTRUMENT CONCEPT FOR THE VLTI

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Abstract. In this presentation we present the concept of an instrument, called V8, capable of combining all eight VLTI telescope coherently. Unlike all existing instruments the concept of V8 is based on mid-infrared heterodyne technologies. These have the potential to considerably simplify the infrastructure of a future large interferometric facility dedicated to planet formation studies such as the Planet Formation Imager. The overall concept and coarse layout of the instrument is presented and we discuss the requested technological building blocks.

Keywords: interferometry, mid-infrared, heterodyne, VLTI, instrumentation, photonics, QCD technologies

1 Introduction

From the birth of stars and planetary systems to supermassive black-holes, the recent observations of astronomical objects at the highest angular resolution have profoundly changed our vision of our surrounding universe. In this field, aperture synthesis with Very Long Baseline interferometry (VLBI) and optical infrared interferometry such as the Very Large Telescope Interferometer (VLTI) are currently the two techniques that provide the highest angular resolution achievable. With its shorter wavelength, infrared interferometry, still confined at 100m scale baseline, could be envisioned as one of the most promising technique to go even further. The extension of this technique to a large number (N$\geq$20) of telescopes and kilometric baselines would represent a major step for observational astronomy. Nevertheless, such an infrastructure, as proposed in the context of the Planet Formation Imager (PFI) initiative (Monnier et al. 2018) will also require challenging technological developments that cannot be extrapolated simply from existing instrumentation (Ireland et al. 2016).

In the current status of PFI, direct interferometry is the privileged option since it provides a major sensitivity gain in the short part of the mid-infrared spectrum (the 3-5 μm window) with respect to heterodyne. A fundamental quantum noise with a dramatically increasing effect at high frequencies explains its poor performance. However, this advantage is less strong in the N and Q mid-infrared bands.

Because it is less demanding on the infrastructure, and because the gain of direct interferometry at $\approx 10\mu$m is not so superior, heterodyne detection offers a still valuable and complementary path to address the problem of kilometric baseline and aperture synthesis with a large number of telescopes. In the past, through the pioneering work of maser inventor and Nobel Prize C.H. Townes and his team, heterodyne detection was the first technique able to combine 2 telescopes in the mid-infrared and to measure closure phases with 3 telescopes, on the Infrared Spatial Interferometer (ISI) in UC Berkeley (Hale et al. 2000; Danchi et al. 2003; Hale et al. 2004). ISI provided valuable scientific results well ahead of its time, anticipating the following generation of direct mid-infrared interferometric instruments such as MIDI and MATISSE. Despite the sensitivity disadvantage in the 10 μm regime by a few factors (and almost none in the Q band), its strength deserves to be further explored, particularly in the context of an array of several tenths of telescopes (Michael et al. 2020).

We present here the idea that mid-infrared heterodyne interferometry is currently the sole technique capable of combining all the eight VLTI telescopes with very limited infrastructure modifications. We describe a concept of a simple instrument, code-named V8 that would bring an unprecedented imaging capability at VLTI, albeit limited to bright sources. It relies on technological advances on many fields pushed by the world-wide interest in developing mid-infrared photonics technologies. Our overarching goal is to push technology towards a complete fiber-linked mid-infrared interferometric facility.

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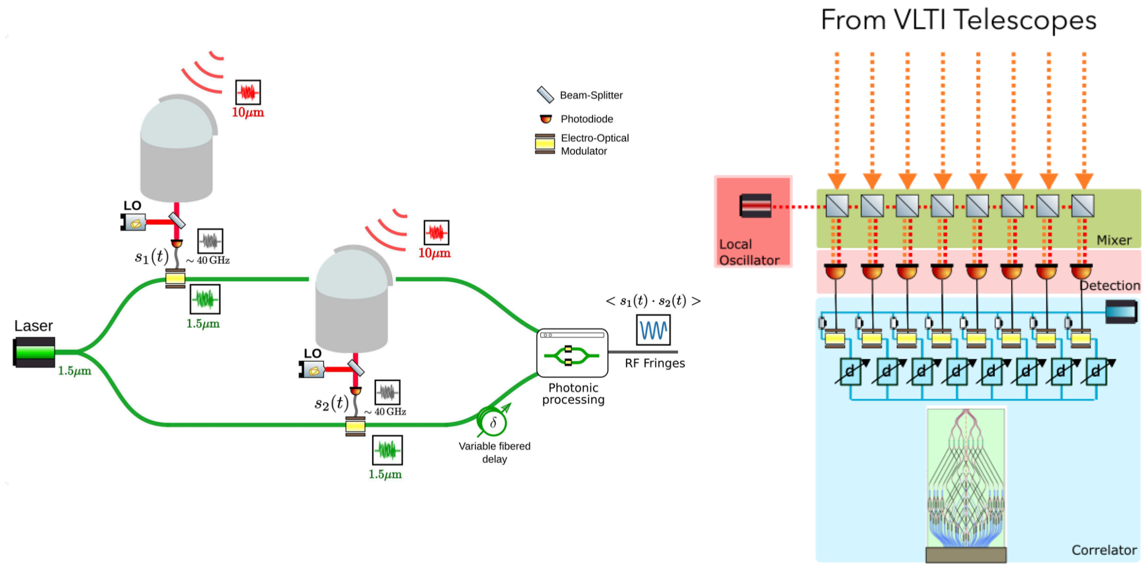

Fig. 1. Left: conceptual scheme of a two telescope heterodyne optical chain Right: schematic of the proposed V8 optical layout inside the VLTI laboratory with the first local oscillator-signal mixing stage, the detection stage and the photonics correlator.

2 The concept

Figure 1 shows a conceptual scheme of a two-telescope heterodyne instrument which forms the basis of our proposition. The incoming celestial light of each telescope interferes (is "mixed") with a local-oscillator on a high temporal bandwidth detector. Local-oscillators are synchronized in phase between the telescopes. In such a process, the mixed mid-infrared signal is down-converted to radio-frequencies signal that can be correlated with other telescopes'. Unlike the classical architecture inspired by radio interferometry, we do not digitize the beating signal but rather use it to modulate a stable laser in such a way that it acts as a carrier of the amplitude information and can be carried through fiber links. We refer to Bourdarot et al. in this conference for a description of this photonics scheme. Interference between the two arms of the fiber link allow a measurement of the correlation between the incoming electromagnetic fields to be made. This provides a direct measurement of the object spatial coherence.

3 The technological building blocks

Other industries such as sensing, telecommunications, time and frequency propagation have considerably pushed forward technologies since the ISI observatory. These developments have reach a sufficient maturity to deserve a thorough examination.

Detection The ISI used $\approx$ 3 GHz detectors corresponding to a $\approx$ 10000 spectral resolution power, which explains partly its limited sensitivity. Improving the detector bandwidth is the first way to increase the sensitivity of the heterodyne scheme as it allows a broader portion of the spectrum to be sampled. We are exploring with Laboratoire de Physique de l'Ecole Normale de Physique (LP-ENS) unipolar mid-infrared ($4\mu\text{m} < \lambda < 12\mu\text{m}$) detectors for a high speed operation up to room temperature Palaferri et al. (2018). These detectors are based on a quantum well absorbing medium embedded into a metallic metamaterial that provides strong sub-wavelength confinement. Such architectures increase the device responsivity and also the detector operating temperature thanks to a reduction of the thermally generated dark current. In addition, unipolar detectors have a unique property which is their very short excited carrier lifetime, on the order of few picoseconds, leading to a frequency bandwidth of several tens of GHz. Using a heterodyne setup made with two quantum cascade lasers, frequency response above 20 GHz have been already demonstrated (Palaferri et al. 2018; Gacemi et al. 2018).

Local oscillator The ISI used a CO_2 laser as a local oscillator (LO) which presents the interest of generating many lines in the 9-12 μm band that can be further enriched depending on the isotope used. In order to further increase the spectral coverage of an heterodyne setup mid-infrared frequency combs should be considered. However, only a few broad bandwidth mid-infrared lasers exist. As a consequence nonlinear frequency down-conversion is the privileged way to generate frequency combs in this spectral region. The specific constraint of the heterodyne interferometric technique requires to generate combs with line spacing corresponding to detector bandwidths which, in our particular case, should be of the order of a few 10GHz. There are currently no commercially available products. However, we note that several applications such as gas sensing, precision spectroscopy and kinetics chemical reactions monitoring require such light sources. With that in mind (Kowligy et al. 2020) have reported the first mid-infrared frequency combs with 10GHz repetition rate around a wavelength of 4 mic and have explored the extension to the 7-11 window using OP-GaP crystals as non-linear conversion material. Other technologies, based on QCL lasers are close to maturity and provide another path for mid-infrared frequency combs (Hugi et al. 2012).

The distribution of a phase-locked mid-infrared local oscillator is another challenge. We note that the recent work by Argence et al. (2015) has demonstrated the possibility to lock a mid-infrared QCL laser to an atomic clock located 47 km away thanks to the phase-controlled propagation of a near infrared ultra-stable laser. The adaptation of this scheme to long-baseline interferometry would not necessarily require the locking on an atomic clock since we are interested in relative phase stability.

Correlation and delay Radio interferometric arrays such as ALMA require correlation techniques that can handle several tens of telescopes with the maximum possible spectral bandpass and resolution. Dedicated electronic technologies are required, starting at the antenna end with high bandwidth digitizers, optical data links to the central correlator. As pointed out by (Ireland & Monnier 2014), the extrapolation of radio-techniques for a mid-infrared array such as PFI lead to not-yet available computing power requirements. Moreover, the perspective of having to deal with high bandwidth RF signals (several 10s of GHz) complicates further the matter. Finally, the bandwidth over frequency ratio being so different between the radio and the mid-infrared, it is highly likely that specific architectures would have to be conceived in order to retrieve the spectral information.

We revisited the idea of carrying an *analogical correlation* by converting the RF signal over to a stable telecom laser carrier using electro-optics modulators. Using off-the-shelf components, we demonstrated that the correlation between two telescopes could be done (Bourdarot et al. 2020). The main interest of this approach is that it provides a simple way to handle both high bandwidth signals (up to 50GHz), many telescopes and several spectral channels with telecom technologies (DWDM). In this conference Bourdarot et al. and in a forthcoming paper (Bourdarot et al. JOSA B under review) present in more detail our photonics analogical approach. The delay compensation can be achieved using commercially available discrete delay line that can generate delays of several 100s of meters and a continuous small range one. Indeed, since we are in this analogical correlation scheme we are limited neither by losses nor by chromatic dispersion.

Fringe tracking As for direct interferometry, heterodyne is subject to the adverse effects of atmospheric piston. This leads to a considerable shortening of the coherence time therefore reducing the integration capability, thus the sensitivity. The only currently known remedy is to stabilize the optical path by providing a dedicated sensor called "fringe tracker". In the context of an all-fibered array such a fringe tracker would need the development of broadband low-loss optical path compensators and dedicated photonics or direct beam combination techniques capable of handling the tens of telescope of the array.

4 V8 simplified layout, implementation and sensitivity

Until a proper way to distribute the local oscillator is demonstrated (this would increase the sensivity by a factor 4) we propose that the 8 beam heterodyne correlator could be entirely located inside the VLTI laboratory. Right of figure 1 shows a conceptual layout of such an instrument. The eight beams originating from the four Unit Telescopes and Auxiliary Telescopes would have to be brought back to the VLTI laboratory. A QCL-based mid-infrared local oscillator stabilized in frequency is distributed and interferes with the incoming celestial light onto the high-bandwidth unipolar detectors. As the laser is polarized, a specific care to the polarization state of the incoming signal would have to be taken. The resulting beating signals modulates the electro-optics modulators of the photonic correlator. We use an 8-beam photonics chip to ensure a pairwise correlation function using the same technique that we used for PIONIER and GRAVITY Benisty et al. (2009); Perraut et al. (2018).

Although the quantum noise still limits heterodyne sensitivity in the N band the gap between direct interferometry and heterodyne can be significantly reduced (and almost cancelled in the Q band). In order to quantify this difference we have compared MATISSE performances as advertised on the ESO official web pages with ISI performances and our putative heterodyne instrument V8. V8 improves on ISI by having state of the art high bandwidth detectors (25 GHz bandpass), better quantum efficiency (0.5) and an improved noise penalty (2) with respect to the one described in Hale 2000.

This analysis leads us to conclude that, despite the systematic better sensitivity of MATISSE with respect to ISI and V8, both heterodyne instruments fare globally well in terms of sensitivity by reaching limiting fluxes compatible with many sources in the southern hemisphere. This is particularly the case for Red Super Giants, Asymptotic Giant Branch stars and post AGB stars for which several tens are significantly brighter than the limits computed here. We note that coupling AT with UTs allows decent limiting fluxes per spectral channel to be obtained. Those are comparable with MATISSE's performance per spectral channel on the AT's.

Our conclusion is that a simple heterodyne instrument at VLTI would be perfectly capable of mapping tens of evolved sources and massive young embedded stars, even without a fringe tracker. Our scientific motivation to pursue this instrumental research avenue is therefore the trade between sensitivity and an incomparable mapping capability since V8 would sample 28 baselines instead of 6 with MATISSE.

5 Conclusion

We have presented a very preliminary concept of an 8 beam instrument that would use mid-infrared heterodyne interferometry to correlate the 8 VLTI telescope thus providing an unprecedented imaging capability at the VLTI. This proposition is based on state of the art technologies and will require further developments and demonstrations but based on expected performances we think it could lead to an actually well performing mid-infrared imager of bright sources while providing an excellent pathfinder for Planet Formation Imager technologies.

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