Improving the performances of current optical interferometers & future designs
Proceedings of Haute Provence Observatory Colloquium (23-27 September 2013)
Edited by L. Arnold, H. Le Coroller & J. Surdej

Heterodyne Interferometry in InfraRed at OCA-Calern Observatory in the seventies

J. Gay[1] & Y. Rabbia[1]

[1] *Observatoire de la Côte d'Azur, UMR CNRS Lagrange, Nice, France*

Abstract. We report on various works carried four decades ago, so as to develop Heterodyne Interferometry in InfraRed (10 μm) at Calern Observatory (OCA, France), by building an experiment, whose the acronym "SOIRDETE" means "Synthese d'Ouverture en InfraRouge par Detection hETErodyne". Scientific and technical contexts by this time are recalled, as well as basic principles of heterodyne interferometry. The preliminary works and the SOIRDETE experiment are briefly described. Short comments are given in conclusion regarding the difficulties which have prevented the full success of the SOIRDETE experiment.

1. Scientific context and technical constraints for InfraRed in the early seventies

InfraRed surveys obtained from ground-based observations have revealed bright sources in this spectral domain, while they were faint or unknown in the visible domain. They are interpreted as stars surrounded by residual matter from a protostellar cloud, which partially (or even totally) absorbs the light from the central star. This circumstellar environment (cooler than the star) radiates in the InfraRed domain, the absorbed energy. The geometry of the stellar environment being unknown (in particular its angular diameter), modeling the radiation processes of these new sources has then become an open issue. An immediate problem was that available facilities and equipments in InfraRed by that time, did not allow measuring these angular diameters which are less than 1 arcsec, (considered at this time as the smallest resolvable angle). Imaging in this range of angular resolution would have needed telescopes with such large diameters as 8m to 10 m (not even in project at that time), adaptive optics systems (yet not defined or not implemented) and bi-dimensional detectors like CCD or CID devices (at the beginning of their forthcoming development). A possible approach for direct imaging could have been the technique of Imaging by Multiplex Encoding (Girard 1970, de Batz et al. 1977), but if it avoids the need for two-dimensional detectors, it does not avoid the need for such large telescopes.

Observation relying on interferometry (which can work with a few small telescopes) appeared then as the only way to reach the angular resolution required for the targeted angular diameters.

Stellar Interferometry basically relies on the measure of the degree of coherence between fields collected by independent telescopes, at several separations and on the use of the Van Cittert and Zernike theorem (Born & Wolf 1975, Rabbia 2005). In other words, it consists of determining discrete values of the spatial spectrum of the source (the Fourier Transform of its brightness distribution).

In InfraRed, two approaches could have been considered: either direct interferometry by mixing optical beams from two telescopes on a unique detector, or heterodyne interferometry, which is transposing to this spectral domain the technique already used by radio astronomers, preserving the phase of the collected fiels and reducing the effect of the huge thermal background from the sky (actually a foreground).

In the InfraRed and visible domains, detection of light is quadratic (incoherent detection). In other words, only the energy conveyed by the electromagnetic field can be recorded, and not its phase, which is the key-information searched for. Direct interferometry (basically a Young's hole scheme), by receiving on the same quadratic detector, two fields collected on separate telescopes, allows in principle to follow the variation of their phase differences (reflecting their optical path differences - hereafter OPD-, continuously changing as the source travels across the sky because of diurnal motion).

Unfortunately this phase difference, highly sensitive to optical paths changes, can not be extracted because a strong spurious phase noise is added by the permanent and random unstabilities caused by the atmosphere and by the instrumental configuration itself. Thus, this approach requires a very demanding control of metrology (OPD's must be less than a fraction of a wavelength) and needs specific techniques (for example fast fast OPD modulation or/and a servo-controlled confiuration, to compensate for unstabilities). Yet, direct interferometry with small telecopes has proven to be efficient in near InfraRed (Mac Carthy et al. 1977, diBenedetto & Rabbia 1987), and in the visible domain (Shao & Staelin 1980, Robbe et al. 1997).

The other choice, the heterodyne approach, is not (at 10 μm) too much perturbated by turbulence and is greatly relaxing the metrology demands. It has motivated to launch two projects in the early seventies, one at Mount Wilson by the Berkeley University, CA, USA (Johnson et al. 1974), the other (Gay & Journet 1975) at OCA (named CERGA at this time).

2. Basic principles of the heterodyne technique

The main feature of this technique is to transpose the frequency of the two collected fields, into a much lower one (so as to allow transmission by cable), while preserving the phase information for each field. This is achieved by receiving on a mono-pixel detector (one for each telescope), a reference field and the collected field. The reference field is named the local oscillator (LO in the following). In our case, it is the light from a CO2 laser around 10 μm). For each frequency composing the incoherent field from the source, an interference process occurs, giving a "beat" signal at a much lower frequency than the one of the fields. The process is described (broad lines) by the sequence of steps listed here below:
One detector at each telescope. Each detector receives LO and the collected field. Superposition of incident fields made by using a BeamSplitter plate with appropriate coefficients for transmission and reflection (LO must be attenuated).

Quadratic detection (time averaged square modulus of the sum of complex amplitudes) Amplification and low-pass filtering. The signals at output are conveyed by cable to a "mixing element" (correlator) delivering a signal proportional to their product, within which the phase difference $\Delta\phi(t) = \phi_1(t) - \phi_2(t)$ between collected fields is preserved. Another appropriate low-pass filtering is performed (for example by a phase-lock amplifier) delivering a signal proportional to the cosine of $\Delta\phi$ which (as already mentioned) varies with respect to time because the source moves across the sky. The process is summarized by the mathematical expressions given below, with indexes "0" and "$*$" respectively for the local oscillator and for the collected field , and is illustrated on Figure 1. The expression of the signal from each detector writes:

$$s(t) \propto \mid A_0 \times exp(i\ \omega_0\ t) + A_* \times exp[i(\omega_*\ t + \phi)] \mid^2$$

where the brackets mean here "filtering by the detection chain". After filtering s(t) by the DC blocking capacitor and the bandpass amplifier, we have the so-called heterodyne signal:

$$s_h \propto A_0 \times A_* \times \cos[(\omega_0 - \omega_*)t + \phi].$$

The term at frequency $(\omega_0 + \omega_*)$, expected from algebra, will be eventually filtered in the detection chain. Now we have two heterodyne signals (from two collected fields) sent to the "mixer" which delivers the correlation signal C(t):

$$C(t) \propto A_0 \times A_* \times \Big(\cos[2(\omega_0 - \omega_*)t + \phi_1 + \phi_2] + \cos(\phi_1 - \phi_2) \Big).$$

This correlation signal is then filtered (low pass) so that we obtain the final output signal $V(t)$:

$$V(t) \propto A_0 \times A_* \times \cos[\phi_1(t) - \phi_2(t)] \qquad (1)$$

where indexes 1 and 2 refer to the telescopes. The frequency of this signal is related to the motion of the source across the sky. A Synchronous Detection device (in-phase and in-quadrature) tuned to the frequency of the fringe signal might be used to follow the fringes, in spite of turbulence effects and to achieve the last filtering. An alternative configuration uses a simple low-pass filtering and a spectrum analyzer. The process (simplified) is schematically illustrated in Figure 1, where DL means Delay Line, used to compensate for the OPD's between collected field, and LPF stands for Low Pass Filter, SA for spectrum analyser. Not appearing in equation (1) are the beamsplitter coefficients (implicitly included in amplitudes A_0 and A_*) and the "degree of coherence γ_{12}" between collected fields, named "visibility", which samples the spatial spectrum of the source,(one sample for each separation of telescopes). From these data, via the "Van Cittert and Zernike" theorem, angular parameters of the source can be calculated. The proportionality factor also comprises the quantum efficiency of the detector and the energy of the photon at frequency ν_0 (local oscillator).

The source has a large spectral distribution so that the heterodyne signal $s_h(t)$ covers a finite spectral interval resulting from the bandpass of the system [detector, DC blocking capacitor, amplifier]. This is schematically illustrated also

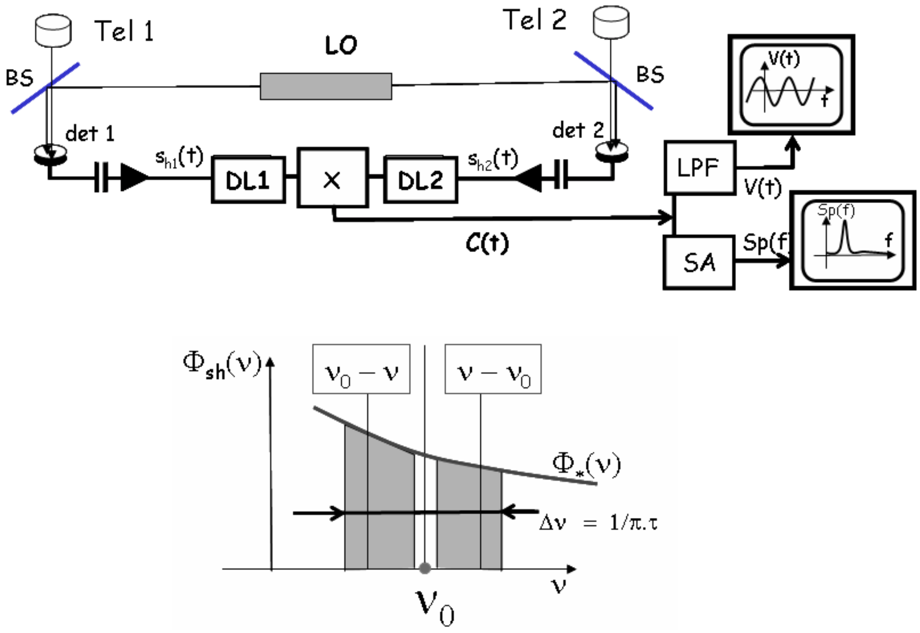

Figure 1.: *Generic set-up and spectral band of work.DL: delay line, LPF: Low Pass Filter, SA: Spectrum Analyzer,* $\Phi_*(\nu)$*: source's spectrum.*

in Figure 1. Note that more than two telescopes can be used at the same time what enables to simultaneously collect several values of the spatial spectrum.

A critical point is the Signal to Noise Ratio (SNR from now). We simply recall here its expression (Assus et al. 1979):

$$SNR = \frac{\eta}{h\ \nu_0} \times F(\nu_0) \times S \times \sqrt{B \times T} \tag{2}$$

where η is the quantum efficiency of the detector, $F(\nu_0)$ is the flux of the source at frequency ν_0, S is the collecting area, B is the electrical bandwidth of the detection chain, and T is the time duration of observation.

3. Preliminary works

We give short descriptions of the set-up and of obtained records for three preliminary observations to prepare the SOIRDETE experiment, which will be described in the next section

3.1 Heterodyne detection in laboratory with a blackbody

The first preliminary work naturally is the detection of a source in the laboratory. The aim of this work is to implement an optical set-up and to test the detection chain (Gay et al. 1973).

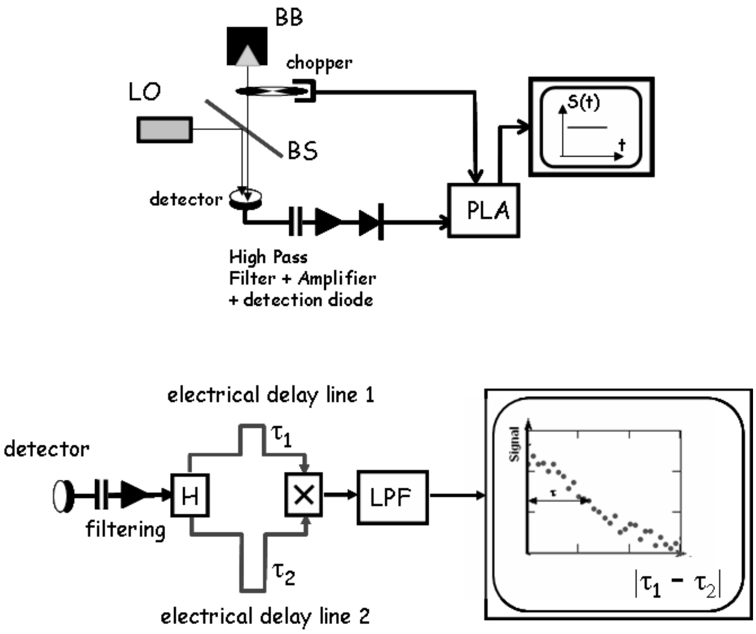

Figure 2.: *Heterodyne detection of a blackbody: detection set-up and auxiliary set-up to measure response time.*

This also allows to optimize adjustments of parameters and to identify from them a standard protocol for handling the set-up. In addition, an auxiliary set-up has been mounted to measure the effective response time of the detection chain, by recording a correlation curve obtained from various phase differences inserted by variable delay lines. The confrontation of the theoretically expectable SNR against the really obtained SNR has proven satisfying. In Figure 2 is shown a schematic description of the generic and the auxiliary configurations.

3.2 Heterodyne interferometry with the Sun

This work essentially aimed at illustrating the principle of the heterodyne interferometry approach and has been seen as a demonstrator, showing a slowly drawn fringe pattern, and needing only a small and simple set-up which does not require components with high performance and large dimension (Gay & Journet 1973).

Actually the interferometer could have been accommodated within the hand, and the variable baseline operated manually. Figure 3 shows a schematic description of the set-up, and a record of the fringe signal versus time. Several recorded fringes and the associated visibility curve drawn on paper (at that time, the communication tools was pretty rustic) are shown in Figure 6 at the end of the paper.

3.3 Heterodyne detection of Arcturus (α Bootis)

The next step in preliminary works was the heterodyne detection of a star (Arcturus, α Bootis). This has been done using the 1.52 m telescope at the Observa-

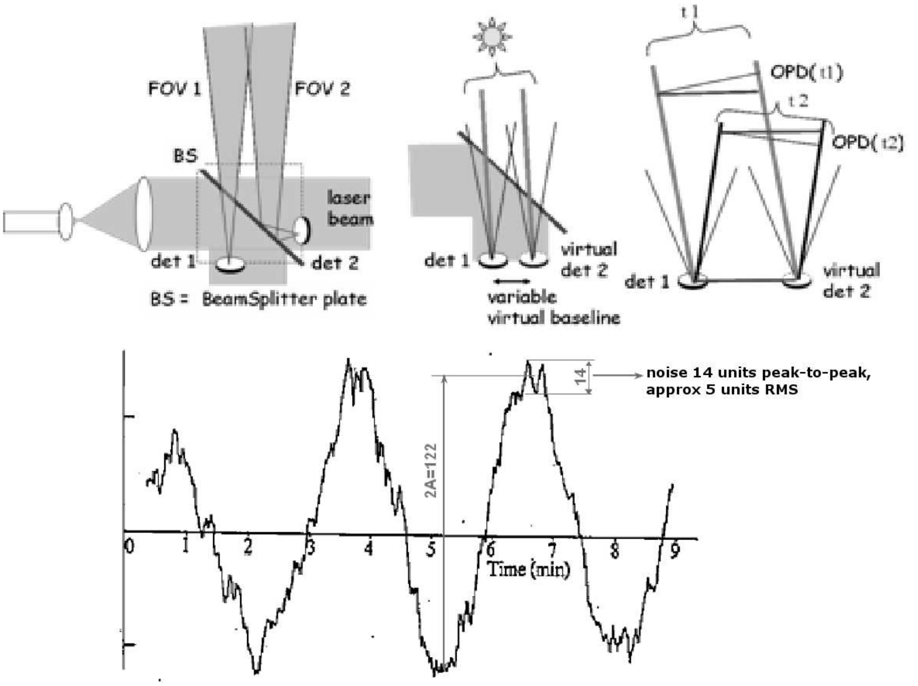

Figure 3.: *Heterodyne interferometry on the Sun, set-up and recording of fringe amplitude. Noise is* $\approx$ 14 *units peak-to-peak, thus RMS noise* $\approx 14/3 \approx 5$ *and SNR* $\approx (122/0.62)/(14/3) \approx 40$ *for visibility V=1 (V=0.62 for solar radius=900 arcsec and baseline=0.75 mm at* $\lambda = 11\mu m$*).*

toire de Haute Provence, France (de Batz et al 1973). Figure 4 shows a recorded trace of the detection.

4. The SOIRDETE experiment

We list here some instrumental features:

- *Telescopes*: two 1 m telescopes, baseline 15 m East-West, what induces change of baseline length seen from the source from 3 m up to 15 m (supersynthesis).
- *Local Oscillator*: CO2 laser, tuned on CO line P56. This apparently interesting line (faintly absorbed by atmosphere) has been the cause of LO instabilities, preventing permanent capability of detection.
- *Detectors*: cooled HeCdTe photodiodes (liquid nitrogen).
- *Amplifier*: electrical bandwidth 5-500 MHz. This comparatively narrow bandwidth allows comfortable coherence length (about 30 cm) but it is detrimental to the SNR.
- Delay lines: set of switchable coaxial lines of various lengths, under computer control.
- *Site*: Calern observatory, a chalk plateau (altitude 1200 m), poor atmospheric seeing in average.

Figure 1, already shown, describes the instrumental functions, while Figure 5 shows the polaroid photograph (displayed as "negative") of the spectrum of the

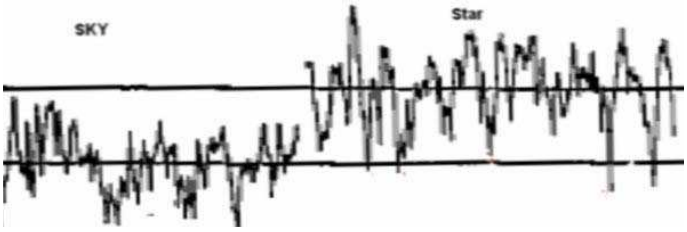

Figure 4.: *Heterodyne detection of Arcturus (α Bootis).*

first fringe signal obtained on Betelgeuse (α Orionis) in August 1978. On the figure 5, the mark F_0 indicates the frequency of the fringe signal.

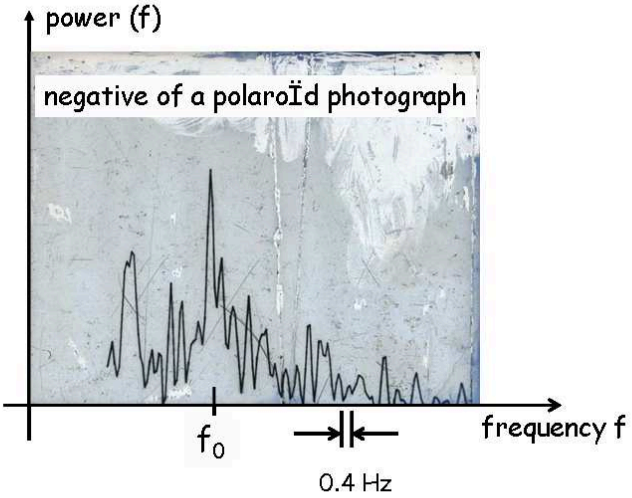

Figure 5.: *Spectral signature of the first fringes obtained on Betelgeuse (α Orionis).*

5. Conclusion

The SOIRDETE experience started in 1972, by the building of two domes, two telescopes and the central laboratory, followed by the progressive implementation of the whole experimental configuration in parallel with some preliminary works. The development has been exceedingly long lasting (more than a decade) what gave time to many failures to occur, distributed over the years and over the whole panoply of the numerous components (some being second hand from lend). The last one, putting an end to the experiment, has been an accident which destroyed the laser, the heart of the system. Among the adverse causes can be noted the frequency unstability of the LO, a bad impedance adaption between the detection

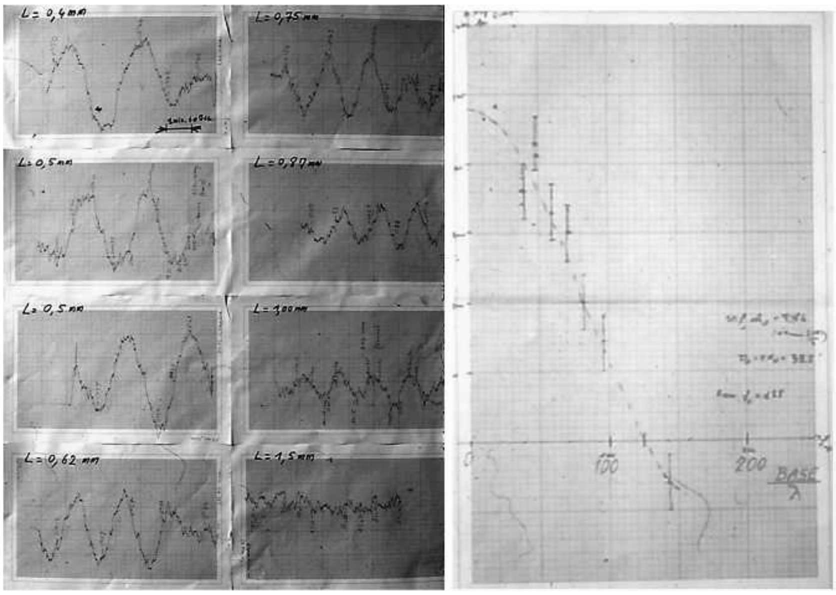

Figure 6.: *Fringes obtained with the Sun as a source, recorded on paper and the resulting visibility curve.*

photodiode and the amplifier (preventing the energy of collected photons to be efficiently transferred) and the rather narrow bandpass of the amplifier, which is (though advantageous regarding the coherence length), correlatively detrimental to the SNR and to the detection capabilities.

Globally it might be noted that in the seventies, modern methods for project management were not popular and not yet well-known. In addition, the pioneering and exploratory nature of SOIRDETE makes them not really applicable in the context, and this has probably been unfortunate. Actually, a detailed analysis of the adverse effects is beyond the scope of this short reminder on the history of SOIRDETE. Today, most of the equipments are used for training activities for students.

Looking at the future, thanks to modern methods of project management and taking into account technological progresses, the heterodyne approach meets a new future, (not limited to InfraRed) regarding the enlargement of the bandpass of the chain, be it by using laser with comb of frequencies or multichannel amplifiers, and by working with dedicated optical fibers and specific numerical techniques.

References

Assus, P.; Choplin, H.; Corteggiani, J. P.; Cuot, E.; Gay, J.; Journet, A.; Merlin, G.; Rabbia, Y. 1979, Journal of Optics, vol. 10, p. 345-350

Born M. & Wolf E. 1976, "Principles of Optics", Pergamon Press de Batz, B.; Granes, P.; Gay, J.; Journet, A. 1973, Nature Physical Science, Volume 245, Issue 145, pp. 89-90

de Batz, B.; Bensammar, S.; Delavaud, J.; Gay, J.; Journet, A. 1977, Infrared Physics, vol. 17, p. 305-310

di Benedetto, G. P., Rabbia, Y. 1987, A&A, vol. 188, no. 1, p. 114-124

Gay J. & Journet A. 1973, Nature 241, 32-33

Gay J., Journet A., Christophe B. & Robert M. 1973, Applied Physics Letters vol. 22, Issue 9

Girard A., 1971, in proceedings of the AGARD conference, CP-90

Johnson M.A., Betz A.L. & Townes C. H. 1974, Phys. Rev. Letters, 33,1617-1620

McCarthy, D. W.; Low, F. J.; Howell, R. 1977, Optical Engineering, vol. 16, p. 569-574

Rabbia, Y. 2006, EAS Publications Series, Volume 22, pp.293-349

Robbe, S.; Sorrente, B.; Cassaing, F.; Rabbia, Y.; Rousset, G. 1997, A&AS, Vol. 125, 367-380

Shao, M.; Staelin, D. H. 1980, Appl.Opt., vol. 19, p. 1519-1522