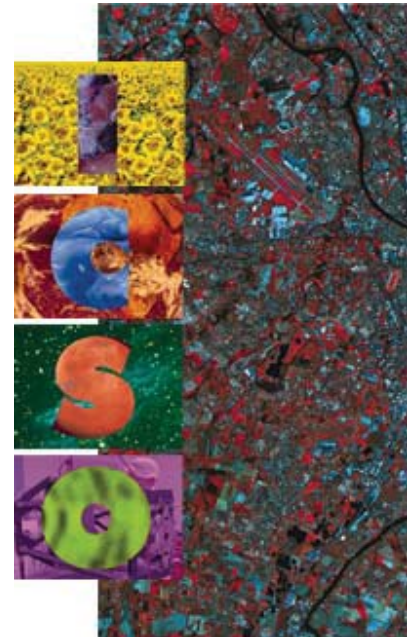


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Nulling interferometry for the darwin mission: laboratory demonstration experiment

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NULLING INTERFEROMETRY FOR THE DARWIN MISSION
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LABORATORY DEMONSTRATION EXPERIMENT

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ABSTRACT - *The DARWIN mission is a project of the European Space Agency that should allow around 2012 the search for extrasolar planets and a spectral analysis of their potential atmosphere in order to evidence gases and particularly tracers of life.*

The principle of the instrument is based on the Bracewell nulling interferometer. It allows high angular resolution and high dynamic range. However, this concept, proposed more than 20 years ago, has never been experimentally demonstrated in the thermal infrared with high levels of extinction. We present here a laboratory monochromatic experiment dedicated to this goal.

A theoretical and numerical approach of the question highlights a strong difficulty: the need for very clean and homogeneous wavefronts, in terms of intensity, phase and polarisation distribution. A classical interferometric approach appears to be insufficient to reach our goals. We have shown theoretically then numerically that this difficulty can be surpassed if we perform an optical filtering of the interfering beams. This technique allows us to decrease strongly the optical requirements and to view very high interferometric contrast measurements with commercial optical pieces.

We present here a laboratory interferometer working at 10,6 microns, and implementing several techniques of optical filtering (pinholes and single-mode waveguides), its realisation, and its first promising results. We particularly present measurements that exhibit stable visibility levels better than 99,9% that is to say extinction levels better than 1000.

1 – NULLING INTERFEROMETRY: OPTICAL REQUIREMENTS AND LABORATORY DEMONSTRATION STRATEGY

The key-points of the ESA's DARWIN mission, a space interferometer to detect extrasolar planets and to perform spectral analysis of them, have been pointed out five years ago, when the project began [Lége 93], [Lége 96]. Among these key-points, the question of an efficient rejection of the stellar light was crucial. We decided thus, to study that difficulty under the point of view of the optical requirements.

The concept of nulling interferometry on which DARWIN is based, was proposed in 1978 by Bracewell to face the problem of detecting faint objects near very bright ones, typically a planet, located 0.1 arcsec away from a 10^7 times brighter star (at $10\ \mu\text{m}$) [Brac 78]. In order to be efficient, the interferometer must have an internal extinction comparable to the contrast that is to say at least 10^5 to 10^6 . In addition, this extinction must be stable.

High values of extinction mean a great similarity of all the incoming wavefronts to be recombined concerning their amplitude, phase and polarisation distributions. However, the different optical paths each beam is going through introduce differential defects on the wavefronts. The consequences are an immediate decrease in the quality of the null at the interferometer output. In this paper, we will only consider the effects of amplitude and phase defects. The question of polarisation has not been considered because the experiment we built to study these last points uses a linearly polarised laser source. The effects of polarisation can be forgotten in a first time.

In order to get a 10^6 rejection rate with a two beam-interferometer, the amplitude (respectively the phase) on each point of the beam recombiner must not differ from one wavefront to the other by more than 0.4 % (respectively 2.10^{-3} radian for the phase) [Olli 99]. Among these specifications, the phase requirements are the most stringent: translated into optical constraints, they lead to a wavefront quality better than $\lambda/3000$ at the working wavelength ($10\ \mu\text{m}$). Even in the optical range, the constraint is still $\lambda/190$. Such constraint can be achievable at reasonable costs on small optical pieces, but not on several 1.5 m class telescopes. This last point was the major difficulty we faced five years ago and that could have killed the project.

One solution to this problem was proposed by J-M. Mariotti and consists in the use of optical filtering of the beams to be recombined [Mari 97]. Two kinds of optical filter can be considered:

- spatial filters: pinholes placed in the focal plane of a lens are spatial filters. They eliminate the high frequencies of the wavefront. Their main drawback is that they are efficient only if the defects to filter are much smaller than the pupil size. Spatial filtering is thus inefficient to correct low order defects such as differential piston, tilt or defocus [Olli 97a].

- modal filters: single-mode optical fibres perform a modal filtering. At the input of the fibre, the beam is reduced over the base of the fibre modes. Since the fibre is single-mode, only the fundamental mode propagates. Whatever the input beam can be, the output beam is the fundamental mode of the fibre. The intensity at the output is thus directly linked to the injection conditions, and the similarity of the beam to the fundamental mode of the fibre. The amplitude and phase defects are theoretically transformed into a global amplitude and phase variation of the fibre mode. This kind of optical filtering allows to correct optical defects over the complete range of scales [Menn 00]. A minimal length of 1.5 m at $10\ \mu\text{m}$ appears necessary to eliminate all the non propagating modes at a level of 10^{-4} [Lepr 00].

This concept is now under test in the visible and a rejection rate of $\sim 10^5$ has been obtained with a compact Michelson interferometer [Sera 99]. A ground based nulling interferometer working in the thermal infrared has been proposed by Hinz et al [Hinz 98] but not with high and, more important, stable values of rejection.

We have built a laboratory interferometer working at 10.6 μm to show high and stable rejection could be obtained in the thermal infrared if optical filtering is used. When we began to design the experiment, optical fibre working at 10 μm did not exist. However, we considered they should be available in the next years or at least small pieces of them allowing first tests. We finally decided to design an interferometer that could work with either spatial or modal optical filters and adopted the following strategy:

- Control of the low frequency defects: piston, tilt, and defocus of the wavefront, global equalisation of the intensity of the beams,
- Optical filtering of the higher order amplitude and phase defects.

This strategy led to a concept of interferometer described on Fig. 1

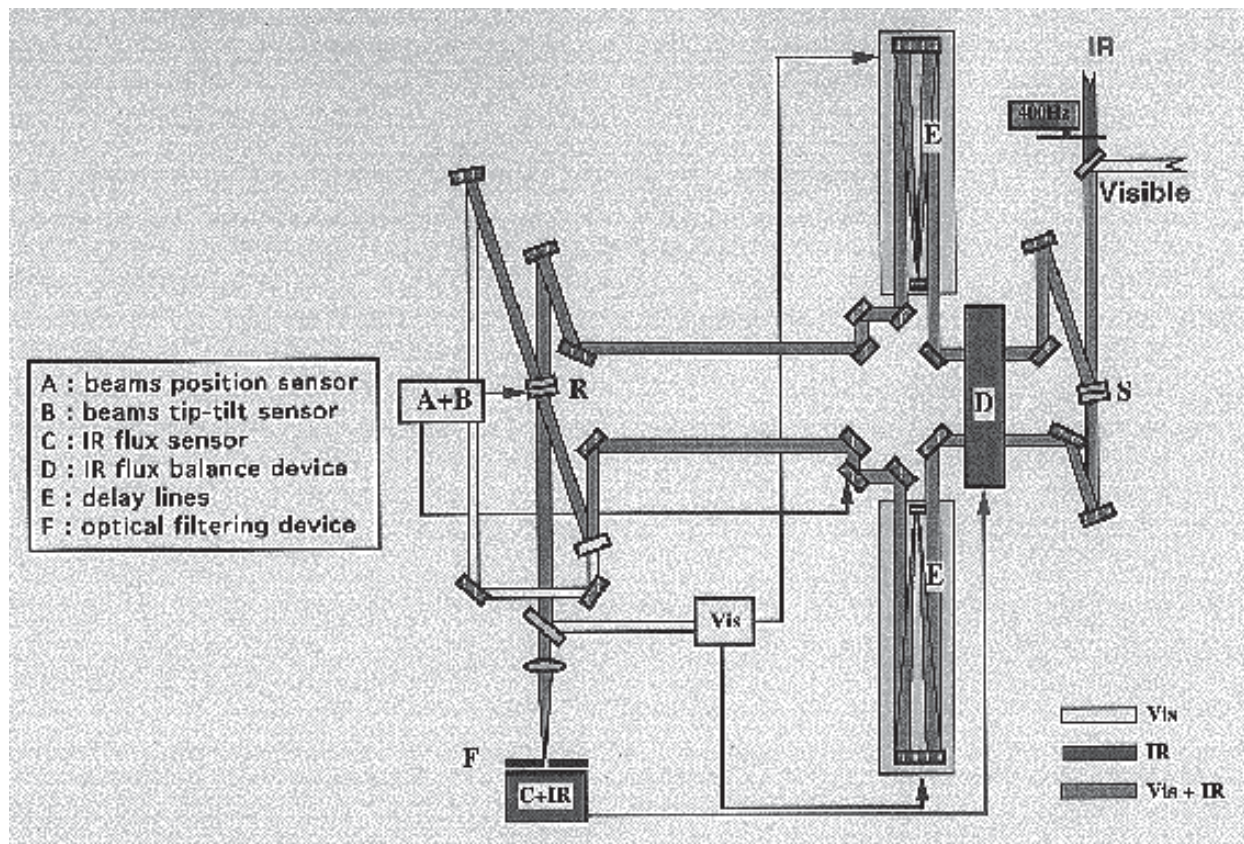


Fig. 1: principle scheme of the demonstration experiment.

2 - DESCRIPTION OF THE EXPERIMENTAL SET-UP

The interferometer we have built is a monochromatic modified Mach-Zehnder interferometer where delay lines, a tip-tilt corrector (angular and lateral superposition of the beams) and an IR flux balancing device (equalisation of their intensity) have been added to allow the two wavefronts perfect overlap and interference. The output signal is sent to an optical filtering device where the superimposed wavefronts are cleaned. The rejection rate is measured as the ratio of constructive interference to destructive interference intensities while the interference state is modulated by modifications of the optical path difference. The interferometer is working in the infrared (CO_2 laser at 10.59 μm), and is servo-controlled using a tuneable visible laser. All its optical elements are $\lambda(\text{vis})/20$ gold coated mirrors for reflective optics and ZnSe or BaF_2 plates for refractive ones.

Each sub-system has been designed and realised to get a 10^6 final rejection rate. The path difference is controlled with an accuracy of a few nanometres over a 1 kHz passband. The tip-tilt

corrector allows the perfect angular (respectively, lateral) superposition of the two beams with an accuracy of 1 arcsec (respectively, 2 μm). The IR flux balance device allows the beam intensity equalisation in a range of $\pm 3\%$ with a relative accuracy of 10^{-3} . The optical filtering bench allows the positioning of either spatial or modal filters with an accuracy of a few μm .

The spatial filters we use are simple metallic pinholes, which diameter varies from a few hundreds to a few tens microns.

The modal filters are small pieces (from 1 mm to several centimetres now) of optical fibres manufactured by the French company "Le Verre Fluoré". Their length appears to be theoretically insufficient to perform a complete modal filtering but taking into account the limited transmission of present materials, it is impossible to use longer waveguides. The geometry of the fibres has been optimised to be single-mode at 10.6 μm . The question to estimate how really single-mode they are, taking into account the very short length, is now experimentally under tests.

Projects to increase the transmission of such filters are under way. Using adapted materials, a few decimetres to metres long optical filters with a reasonable transmission at 10.6 μm can be expected in the near future [Perr 00]. A more complete description of this interferometer and particularly, all its sub-systems has been done by Ollivier et al. [Olli 99], [Olli 00].

3 - FIRST RESULTS

The experiment has been completed at the beginning of October 1999 and is now under development and use. It is shown on Fig. 2. Several preliminary tests have been presented during the ICSO'97 [Olli 97b].

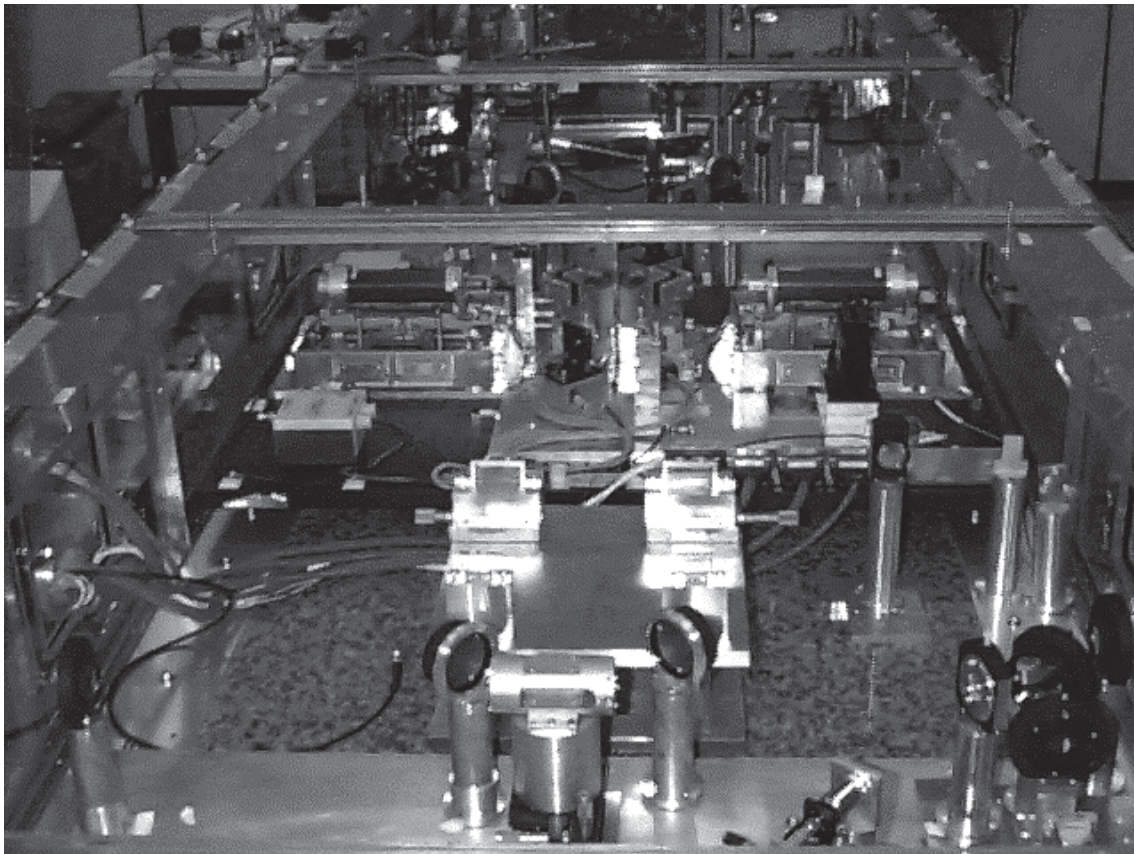


Fig. 2: General view of the interferometer. From the foreground to the background, the beam-splitter, the intensity balance device, the delay lines, the tip-tilt corrector, the beam-recombiner and the optical filtering device.

The first measurements of contrast in the IR have been performed using spatial filters only. They have been presented during the DARWIN and Astronomy conference. At that time, we exhibited a rejection rate better than 10^3 , but relatively noisy. The origin of the noise was mainly the turbulence over the set-up (the optical path is longer than 4 m in each arm). At that moment, the thermal control of the enclosure was not used. The protective enclosure was namely open to allow the settings. The path difference control was performed manually, and all the servo control loops were open.

Since the end of November 1999, we have developed the set-up in two directions:

- improvement in the settings and alignment of the beams: more than 15 reflections and transmissions are used on each beam and require perfect settings,
- time-stabilisation of the null.

The first point was achieved using the infrared camera CAMIRAS from the CEA. Its 128x128 CCD helped us to monitor our beams over the optical path and to eliminate the major sources of vigneting. This operation, associated to the use of a more powerful laser lasing at $9.6 \mu\text{m}$ and providing about 1 W at that wavelength increased the S/N ratio by a factor better than 100.

The second point has been reached by the use of the heating enclosure. A vertical temperature gradient, imposed by the presence of a protective enclosure heated from the top, allowed to reduce drastically the laboratory turbulence, and thus, the phase noise, allowing to stabilise the null at a value better than 10^3 during more than 3 minutes (Fig. 3).

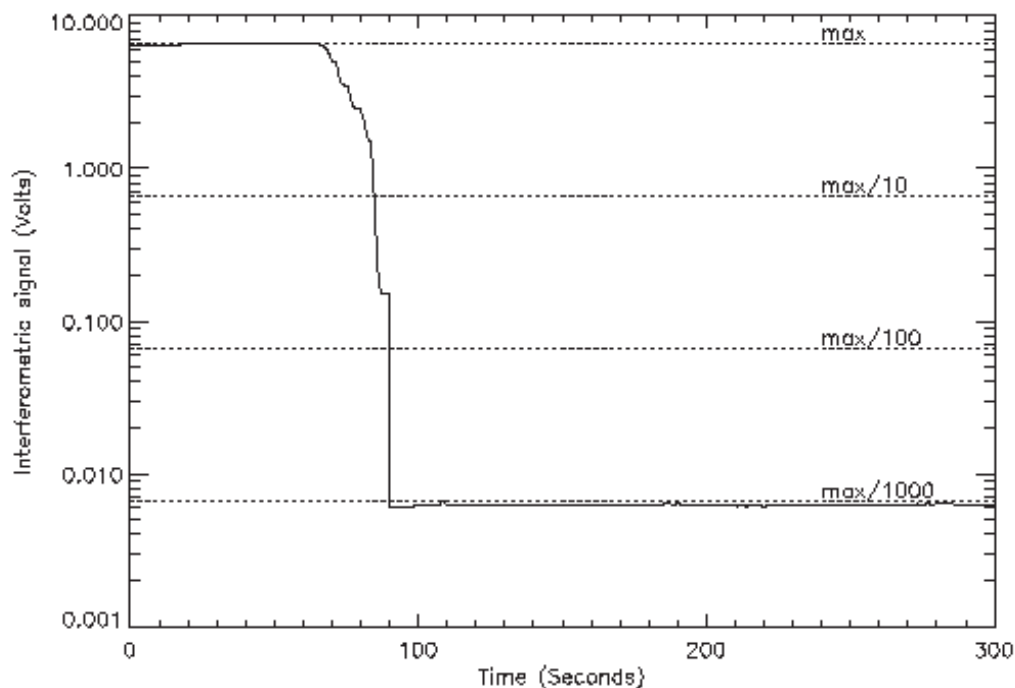


Fig.3: Evolution of the intensity at the output of the system, in constructive and destructive interference states. The recording reveals a stable rejection better than 1000 during more than 3 minutes without any path difference correction or servo-control system.

This stable value of 10^3 is not enough to demonstrate the validity of the principle for the detection of stellar companions in that range of wavelengths. However, we have serious reasons to hope for an improvement in these results. The interferometer is still under development, and lots of

parameter can be improved, like the optical filtering devices, the optical path difference control, and the beams superposition accuracy.

4 - FUTURE PLANS AND DIFFICULTIES

The short-term goal for this demonstration experiment is to reach 10^4 to 10^6 rejection rates in a monochromatic case (the interferometer is illuminated by a laser). This goal should be reached in the next months particularly with the development of new modal optical filters.

The next step is to widen the spectral range of the null. The main problem is the difficulty to find bright sources in that range of wavelengths, where the detection is quickly limited by the thermal background. In the monochromatic case, this problem was eliminated by the use of a laser that concentrates fully coherent energy in a collimated beam with a high surface brightness.

Another problem is the achromatic phase shift to get the null. Several solutions have been proposed:

- dielectric plates [Ange 97],
- rooftops [Shao 92],
- focus crossing [Gay 96].

Our demonstration experiment will have to integrate such a device. At present, the phase shift is obtained by path difference that is highly chromatic. The optimal solution has not yet clearly been determined, and each method is under test by several groups in the world.

The technological challenges induced by nulling interferometry are severe, but this new type of instrument should open horizons in the dark objects astronomy in the next years and decades.

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