

A Fibered Large Interferometer On Top of Mauna Kea :

OHANA,

the OPTICAL HAWAIIAN ARRAY FOR NANO-RADIAN ASTRONOMY

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ABSTRACT

The Mauna Kea site houses two eight-meter and two ten-meter class telescopes which will soon be fully operational. In addition to other existing large telescopes already available, the Mauna Kea summit offers a unique opportunity to build a large optical and infrared interferometer in the northern hemisphere with both the highest angular resolution and the highest sensitivity. We discuss the possibility to recombine with single-mode fibers this array whose large telescopes will all be equipped with adaptive optics facilities. We show the tremendous potential of this instrument for astrophysics and how complementary it is to other large arrays now under construction.

Keywords: Interferometry, aperture synthesis, infrared, single-mode fibers, adaptive optics

1. INTRODUCTION

The site of Mauna Kea is unique in several respects. The quietness and transparency of its atmosphere make it one of the very best ground based sites for astronomy. It is now an impressive collection of large telescopes including Keck I and Keck II (10 meters), Gemini and Subaru (8 meters), IRTF, CFHT, and UKIRT (3 to 4 meters). These telescopes cover an area 800m x 300m in size along a North-West axis. The site and telescopes characteristics are compatible with a high angular resolution and sensitive interferometric array as proposed by Mariotti et al. (1996)¹ and named OHANA, the hawaiian word for family and which stands for Optical Hawaiian Array for Nano-radian Astronomy.

The goal of the present paper is to give an update of the project. A complete rationale for OHANA was already given in two publications^{1,2}. We here simply recall the two technological breakthroughs which make the realization of the interferometer possible :

- Adaptive optics: the large Mauna Kea telescopes are already or are being equipped with adaptive optics systems providing Strehl ratios of at least 0.3 at 2 μm on sources as faint as $R=14$ ^{3,4,5};
- Single-mode fiber optics: they allow to transport and combine beams with an absolute visibility calibration quality as good as 0.3%^{6,7}.

Adaptive optics ensure a high sensitivity and efficient use of the large pupils. Fiber optics permit beam transportation over hundreds of meters otherwise difficult in the Mauna Kea environment.

We first present some preliminary science drivers which make OHANA a unique tool for some astrophysical issues. We then present a technical description of the array and show the feasibility of all subsystems. Next, we discuss an estimate of the performance of OHANA to show how they meet the science goals. Eventually we present the possible phases of the project.

2. SCIENCE DRIVERS

The new generation interferometers (Keck and VLTI) will have relatively long baselines (up to 200 meters) compared to most of previous interferometers except SUSI. Thanks to their big apertures, they will have a much larger sensitivity and will open the field of very high angular resolution on faint sources otherwise out of reach. AMBER, the near-infrared beamcombiner of the VLTI, and the 2 micron instrument of the Keck interferometer will have a maximum sensitivity of about $K=14-15$ ^{8,9} on axis and up to $K=21$ if an off-axis bright source is used as a reference. Thanks to smaller 1.8 meter

outrigger telescopes, the maximum resolution will be of 2 mas (with VLTI at 2 microns). Yet, the maximum sensitivity will be obtained with the larger apertures but with shorter baselines limiting the best resolution to 5 mas on Keck and 3 mas on VLTI.

For very compact or distant sources, a higher resolution at equivalent sensitivity is still required. As a matter of facts, among other science topics, the study of AGNs and YSOs require the limit of 1 mas to be broken. The largest baseline of OHANA (Subaru-Gemini) has a length of 800 meters yielding resolutions of 0.25 and 0.5 mas at 1 and 2 microns, respectively therefore opening the field.

In YSOs, Keck and VLTI will resolve the accretion disk around the central forming star. Yet, it is important to get access to regions closer to the stellar disk where it interacts with the new born star and where collimated jets form. The nature of the source of energy of jets is not well known and forbids a complete understanding of the final stages of star formations. In order to address this new field, a linear resolution on the order of the stellar disk (about 0.1 AU) is required. For the closest YSOs regions (150 pc distance), OHANA will provide resolutions of less than 0.1 AU and will resolve the inner part of the disks and the stars themselves.

In AGNs, characteristic sizes for the dust torus, the Broad Line Region and the accretion disk are 10pc, 1pc, 0.01 pc respectively. For the closest object, NGC1068, VLTI and Keck will resolve the BLR. On all other sources, they will see no spatial scale smaller than that of the dust torus forbidding access to the inner regions of the central engine. In order to resolve the BLR and get informations on the accretion disk, a linear resolution of less than 1 to 0.01 pc is mandatory. The diagram in Figure 1 shows that the distribution of Seyfert galaxies observable with giant interferometers peaks at 100 Mpc where the maximum linear resolution of OHANA is 0.2 pc at 2 microns. For most of objects, OHANA will therefore provide enough resolution to study the BLR. For closer objects, accretion disks will also be studied (the linear resolution is 0.02 pc at a 10 Mpc distance) either directly or by model fitting.

The YSOs and AGNs programs alone provide OHANA with a unique scientific niche unaccessible to any other array anticipated in the next decades (either ground based or space based). It is to be noticed that the high angular informations collected by OHANA will be complementary to that of VLTI and Keck and they will therefore be useful to interpret their data.

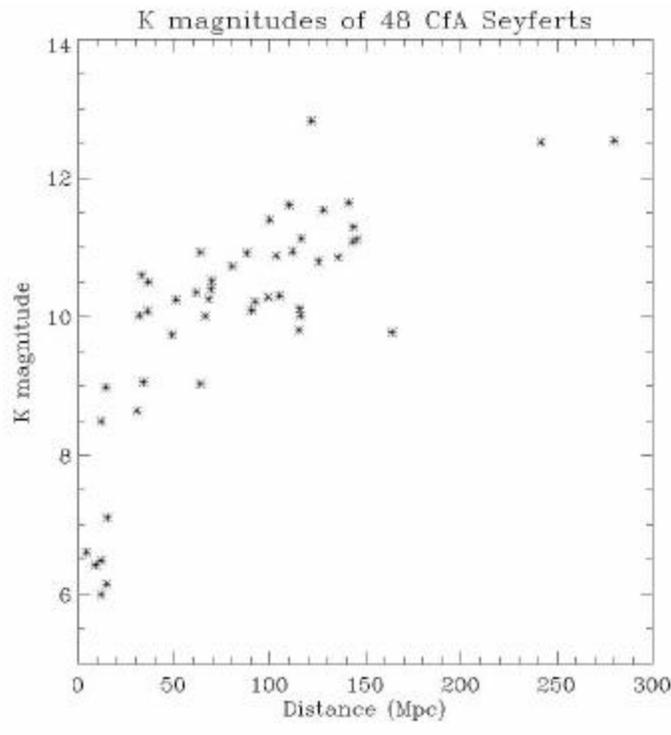


Figure 1: Distribution of Seyfert galaxies in a K vs. Distance plot from the CfA catalog.

3. TECHNICAL DESCRIPTION

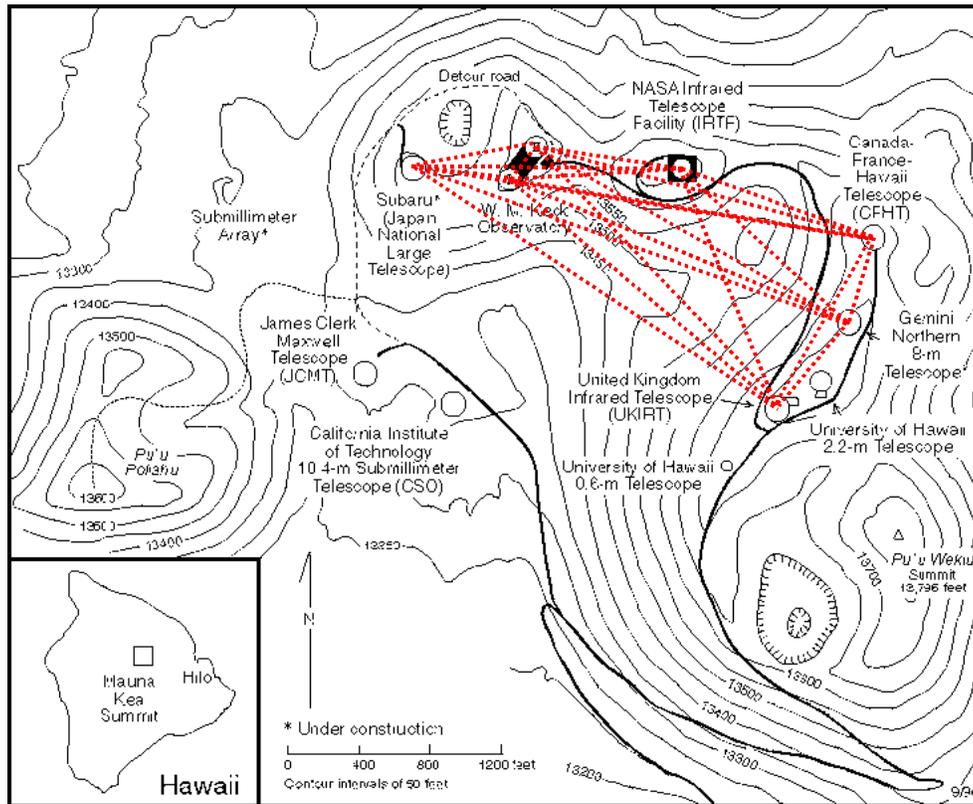


Figure 2: Map of the Mauna Kea summit. Optical telescopes larger than 3 meters have been connected with dotted lines to show all possible baselines configurations in OHANA.

3.1. Array

A map of the Mauna Kea summit is presented in Figure 2. The OHANA array can potentially comprise 7 telescopes larger than 3 meters. The longest baseline is between Subaru and Gemini and has a length of 800 meters. The shortest one connects the two Keck telescopes. Although the telescopes were not arranged in an interferometric array a good (u,v) coverage can be achieved¹. The larger telescopes of the array mostly produce East-West baselines. From this point of view, inclusion of the smaller 4-meter class telescopes is important to provide shorter and intermediate baselines and North-South extension.

Because of site constraints, it will not be possible to equip the array with delay line tunnels and beam combining laboratories. It is therefore necessary to find solutions for beam transport and delay which fit with this requirement.

3.2. Subsystems

The whole interferometer can be broken down into several subsystems. Most of subsystems are readily working on several interferometers and are consequently not a matter of concern. Among subsystems, the delay line requires a dedicated study since it will have to produce large delays and fit into existing built facilities.

3.2.1. Beam extraction at telescope focus

The critical part in single-mode (fiber) interferometry is the injection of light into the spatial filter. The maximum coupled energy is proportional to the instantaneous coherent energy which, under weak turbulence ($D < r_0$), is roughly equal to the Strehl ratio. In OHANA, this part will be made easy by adaptive optics systems thanks to which beams will be stable and with high Strehl ratios.

Depending upon telescope configuration, beams will be extracted at the Cassegrain or at the Nasmyth focus. In order to maximize flux coupling in fibers, AO systems will have to be optimized to take into account the apodization of the pupil by the main mode of the fiber¹⁰. Coudé et al. (2000)¹¹ have demonstrated the power of adaptive optics for fiber coupling as a gain of 37 was obtained with the ADONIS system turned on on the 3.60 m telescope at ESO, La Silla.

The fiber will be placed directly downstream from the AO system. The corrected beam f-ratio will be adapted to that of the fiber to maximize coupling efficiency. Four degrees of freedom are then required to align the telescope beam with the fiber mode (2 for pupil position and 2 for image position). The 2 image plane adjustments will be motorized to permit remote fine tuning of the injection. Initial positioning of the fiber will be done by superimposing it with that of the reference source of the AO.

The fibers can extract two fields which can be multiplexed and carried by a single fiber. Dual beam extraction techniques have been studied and realized for PTI and will be used on both Keck⁹ and VLTI¹². The second field is useful to cophase the pupils and improve the sensitivity of the instrument by about 5 magnitudes (thanks to a gain of x100 in exposure time). Multiplexing can be achieved with polarizations, wavelength mixing or frequency coding of the signals.

After extraction, the beams will be transported to the base of the telescope in a single-mode fiber.

3.2.2. Beam transportation

Beams will be transferred from each telescope base to the recombination unit with single-mode fibers. No relay optics are needed hence no infrastructure needs to be built. Fibers will travel underground in existing telecom ducts.

The low attenuation of existing fiber components allow to anticipate high transmission levels. Silica fibers, well suited for the visible and near-IR domains (up to 1.6 μm), have a negligible attenuation over kilometric distances. Fluoride glass fibers, for use above 1.6 μm , have attenuations of 1-2 dB/km yielding an average transmission of 70% in the K band for a kilometer-long baseline. These performances are to be compared with the transmission of an optical train requiring a few tens of reflexions to carry the beams.

As long lengths of fibers will be used, it will be necessary to compensate for differential dispersion for each baseline of the interferometer. Fiber dispersion compensation has been demonstrated for both silica¹³ and fluoride glass fibers¹⁴. One may fear fiber lengths variations on such long paths. Yet, thermal expansion coefficients for silica and fluoride glass fibers are quite small ($\sim 10^{-5} \text{ K}^{-1}$) leading to centimetric differential lengths variations on the longest baseline in the less favorable case (homogeneous temperature variation along a single fiber cable). Since the temperature variations will not be homogeneous along a single cable and cables will be placed underground making temperature stable and, eventually, since those effects will probably be comparable in both fibers in a same baseline, it is likely that the magnitude of the differential effect will be small. Besides, accurate fiber length control has been already demonstrated and is therefore not a concern⁸. Fibers can be stretched with piezo cylinders very accurately to compensate for possible differential dispersion variations changes.

For the same reasons, polarization could also be a concern because of temperature variations and telescope pointing-induced stresses variations. But it is possible to use polarization maintaining fibers and split polarizations before beam transportation. Regular fibers can also be used if polarization can be controlled and its effects cancelled.

3.2.3. Delay lines

Long delays are necessary. In order to achieve the required few hundred meters delays a combination of slew-and-clamp and continuous delay lines will be used. Thanks to the use of single-mode components, optics will have a small size permitting to achieve compact designs which will fit in the already existing buildings. Long delays can be produced if the beams are folded several time. The slew-and-clamp characteristic of long delay lines makes them relatively easy to design since no active control of the generated delay is required. The long delay line needs to be studied but the technical difficulty is not prohibitive. The outputs of the fibers being fixed, no extra dynamic control of pupil nor image is required. Already existing systems to produce continuous delays to compensate for Earth rotation will be used and do not require any further development.

3.2.4. Beam combiner

An all-single-mode fibers beam combiner has demonstrated capability to produce high quality science data⁶. An alternative solution may be provided by the use of integrated optics¹⁵. Beams will be recombined with X couplers playing the role of classical beam splitters. Beams will be recombined in the co-axial mode and the phase modulation in the fringe pattern will be produced by opd generation with a fast moving mirror (mirror mounted on a piezo stage e.g.).

Photometric fluctuations will be measured to accurately calibrate visibilities. Good quality visibilities will allow to study objects with a relatively small number of visibility points measured at different baselines and to choose between different models of the sources.

3.2.5. Assessment of subsystems performance

One of the interests of single-mode fibers is that they make all subsystems fully independent from each other. Once light has been injected at the focus of the telescopes, the whole interferometer loses memory of the telescopes. This also applies to the beam combiner which is independent of all upstream subsystems. Subsystems are linked to each others by simple connectors causing small losses (2%). All subsystems can therefore be tested and optimized independently before they get connected to each others. Eventually, the whole system (except for the telescopes) can be tested with an artificial source during day or night time to find the internal metrology and to measure time/temperature/stress dependent quantities without requiring expensive telescope observing time. In the end, the internal source is replaced by the beams provided by the telescopes to observe objects and measure visibilities.

4. ANTICIPATED PERFORMANCES

4.1. Wavelength range

Single-mode fibers can be used to transmit light on long distances from the visible to the infrared. A potential wavelength coverage for OHANA therefore ranges from 0.4 to 4 microns. Extension to longer wavelengths will be made more difficult because of background fluctuations and poorer fiber transmission. It is likely that the K band will be a first higher limit in wavelength. Besides, AO systems will have better performance at this wavelength than at shorter wavelengths. Although the AO correction will be poorer at shorter wavelengths, worse coupling efficiencies may be compensated by a better detection sensitivity. In this respect, the wavelengths to start with will be in the 0.9-2.5 microns range.

4.2. Spectral resolution and field of view

For most of potential programs, the astrophysical targets of OHANA are faint and cannot accomodate high spectral resolution before the dual star feed mode is available. OHANA is particularly well suited to observe compact sources which do not require an important imaging capability. In theory, the interferometric field of view is limited by spectral resolution (it is the product of spectral by spatial resolution: $\lambda/\Delta\lambda \cdot \lambda/D$). Although compact, AGNs and QSOs luminosity distributions extend far away from the central core. In theory, it is therefore required to increase spectral resolution to increase the field of view. Yet, the ratio of baseline to telescope diameter is large in OHANA implying that the light collected by the single-mode fibers will cover areas on the sky fully resolved by the interferometer. For compact objects, regions outside the central core will not produce any visibility power with the net result of decreasing the visibility level of the central core in the ratio of relative intensities. By sampling the visibility of the central core at different baselines, the constant “background” of visibility produced by the resolved regions can be removed. It is then not absolutely necessary to disperse light. It is remarkable that for AGNs 100Mpc away, the size of the BLR is 1pc i.e. 5 times the resolution of the longest baseline. Given that the spectral resolution of the full K band filter is 5, the interferometric field of view is globally well adapted to the size of the central core. For the closest objects, only a moderate increase of spectral resolution may be necessary. When it will be possible to fringe track on a bright object in the differential piston isoplanatic field, moderate spectral resolution will be possible to increase the interferometric field of view on fainter objects, if necessary.

4.3. Sensitivity

Sensitivity is mostly governed by the capacity to detect the photons injected into a single-mode fiber. A sensitivity estimate on signal detection can be worked out rapidly with the following formula:

$$SNR = Ph \cdot \rho \cdot T \cdot QE \cdot f_s^{-1} / RON$$

where Ph is the rate of photons per second, ρ is the coupling efficiency in fibers, QE is the quantum efficiency of the detector and RON the read out noise, and f_s is the sampling frequency of the fringe signal. We can compute an estimate of SNR in the K band for example for an object of magnitude K , an 8 meter telescope assuming $QE=50\%$ and $RON=1e^-$ and $\rho=20\%$ (for a Strehl ratio of 0.3 and a 30% loss due to the central obstruction). This yields:

$$SNR = 1.3 \cdot 10^{10} \cdot 10^{-0.4K} \cdot T \cdot f_s^{-1}$$

Assuming that the signal can be detected with a SNR of 5, this yields as limiting magnitude:

$$K_{lim} = 23.5 + 2.5 \text{ Log}(T/f_s)$$

From the transmission of the single-mode fluoride glass fibers on 1km and the possible transmission of the slew-and-clamp delay line (on the order of 10 to 20 reflections to produce a few hundreds of meters of delay in one of the already existing buildings) one can estimate T to be on the order of 25%. The fringe frequency will depend upon the frequency cut-off of coupling efficiency fluctuations and of piston speed. Actual average sampling frequency on FLUOR is of 1500 Hz. This yields a first limiting magnitude of $K_{lim}=14$. Yet, it is well known that sensitivity prediction for interferometers remains a challenge. An interferometer is a collection of many subsystems whose coordinated operation is difficult to anticipate. And moreover, interferometers are complex optical systems whose transmission can in practice be far from pre-calculation results. Since the transmission and sampling frequency parameters are probably the most difficult to determine, we have plotted in Figure 3 K_{lim} vs. T and f_s for two values of each parameters: a pessimistic estimate ($T=1\%$, $f_s=1500\text{Hz}$) and an optimistic estimate ($T=10\%$, $f_s=50\text{ Hz}$). The area enclosed by these for laws contains the probable value of the limiting magnitude of OHANA in the K band.

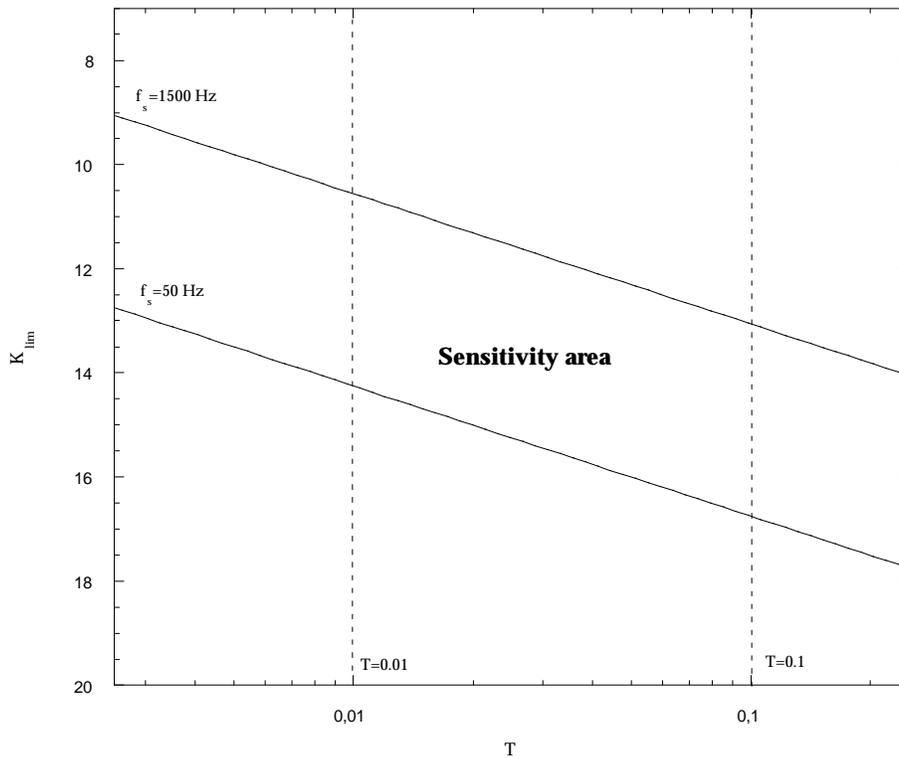


Figure 3: Study of the sensitivity of OHANA in the K band as a function of overall transmission and sampling frequency. The central area is an estimate of the probable range of sensitivity.

An extrapolation from the FLUOR sensitivity would yield $K_{lim}=12$ which is in the sensitivity area. But this would probably be pessimistic since the detector used for FLUOR has a poorer sensitivity than more recent detectors and the triple coupler has a poor transmission.

With a bright off-axis source, the limiting magnitude will be extended by 5 magnitudes. As these simple calculations show, the sensitivity of OHANA will allow to address most of the sources of the program.

5. PROJECT

Recently, a first meeting hosted by CFHT was organized in Hawaii with some potential OHANA participants (CFHT, Keck, Gemini, University of Hawaii, NASA and Paris Observatory). In the conclusions of the meeting, phases have been identified to initiate the OHANA project. A first phase will consist in designing an injection module and to test it at some of the telescopes. Use of AO systems will be optimized for fiber coupling. In a second phase, short telescope pairs will be coupled to demonstrate feasibility of OHANA. First generation subsystems (delay lines, beam combiner, single-star injection

modules) will be used. The third phase will be the realization of the whole OHANA project. The first phase will start in the second half of 2000. The goal is to complete the second phase by 2001-2002.

New participants to OHANA are welcome!

6. REFERENCES

1. J.-M. Mariotti et al., "Interferometric connection of large ground-based telescopes", *A&AS* **116**, 381, 1996
2. J.-M. Mariotti et al., "Interferometric connection of large telescopes at Mauna Kea", *SPIE* **3350**, 785, 1998
3. P.L. Wizinowich et al., "Performance of the Keck Adaptive Optics Facility: the first year at the telescope", these proceedings, paper 4007-64
4. J. Graves et al., "First light for Hokupa'a 36 on Gemini North", these proceedings, paper 4007-65
5. O. Lai et al., "CFHT adaptive optics: first results at the telescope", *SPIE* **2871**, 859, 1997
6. G. Perrin et al., "Extension of the effective temperature scale of giants to types later than M6", *A&A* **331**, 619, 1998
7. V. Coudé du Foresto et al., "The FLUOR/IOTA fiber stellar interferometer", in *Integrated Optics For Astronomical Interferometry*, Grenoble, Observatoire de Grenoble, P. Kern and F. Malbet eds., 110, 1996
8. R. Petrov et al., "AMBER: the near-IR focal instrument of the VLTI", these proceedings, paper 4006-07
9. M. Colavita, P.L. Wizinowich, "Keck interferometer: progress report", these proceedings, paper 4006-34
10. C. Ruilier, "Filtrage modal et recombinaison de grands télescopes. Contributions à l'instrument FLUOR", PhD thesis, université Paris 7, 1999
11. V. Coudé du Foresto et al., « Using single-mode fibers to monitor fast Strehl ratio fluctuations. Application to a 3.6 m telescope corrected by adaptive optics », accepted for publication in *A&AS*
12. F. Delplancke et al., "Astrometry with the VLTI", these proceedings, paper 4006-41
13. F. Reynaud, J.J. Alleman, P. Connes, *Applied Optics* **Vol. 31 N. 19**, 3737, 1992
14. G. Perrin, "Une unité de recombinaison à fibres pour l'interféromètre IOTA. Application à l'étude des étoiles de type tardif", PhD thesis, université Paris 7, 1996
15. F. Malbet et al., "Integrated optics for astronomical interferometry. I. Concept and astronomical applications", *A&AS* **138**, 135, 1999