Bull. Astron. Soc. India (2000) **28**, 175-209

Perspective of long baseline optical interferometry

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Received 10 January 2000 ; Accepted 21 February 2000

Abstract. This article is a sort of sequel of the earlier extensive review by Saha (1999a) where emphasis was laid down on the ground based single aperture, as well as on the working long baseline optical interferometers (LBI) situated at the various observatories across the globe that are producing a large amount of astronomical results. Since the future of high resolution astronomy lies with the new generation of arrays, the numerous technical challenges of developing such systems are addressed indicating the current trends and the path to future progress in interferometry. The new generation interferometers such as Palomar testbed interferometer (PTI), Navy prototype optical interferometer (NPOI), Keck interferometer, Very large telescope interferometer (VLTI), Center for high angular resolution astronomy (CHARA) array, Optical very large array (OVLA), Mitaka optical infrared arrays (MIRA), etc., are being developed. A few of them, viz., PTI, NPOI, IOTA are producing results. Among the working interferometers that have been described earlier by Saha (1999a), the expansion of the Grand interféromètre à deux (two) télescopes (GI2T), Infrared and optical telescope array (IOTA) are in progress. The current status of all these interferometers stated above are enumerated. The data analysis being carried out using the working interferometers are also described. The space interferometry programmes are advancing very fast. Among the notable ones are the Space technology 3 (ST3), Space interferometry mission (SIM), and Darwin; they have already received funds. The technical details of these interferometers and their objectives are highlighted.

Key words: optical interferometry, arrays, space interferometry, astrometry.

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1. Introduction

The implementation of imaging by interferometry in optical astronomy is a challenging task. Though interferometry at optical wavelengths in astronomy began more than a century and a quarter ago (Fizeau, 1868), the progress in achieving high angular resolution has been modest. The first successful measurement of the angular diameter of α Orionis was performed in 1920 using stellar interferometer (Michelson and Pease, 1921), but the field lay dormant until it was revitalized by the development of intensity interferometry (Brown and Twiss, 1958). Over the last few decades, a marked progress has been witnessed in the development of this field, offering to realize the potential of the interferometric technique.

Single aperture speckle interferometry (Labeyrie, 1970) decodes the diffraction-limited spatial Fourier spectrum and image features of the object. A profound increase has been noticed in its contribution (Saha, 1999a and references therein) to measure fundamental stellar parameters, viz., (i) diameter of stars, (ii) separation of close binary stars, (iii) imaging of emission line of the active galactic nuclei (AGN), (iv) the spatial distribution of circumstellar matter surrounding objects, (v) the gravitationally lensed QSO's, etc., (Saha, 1999a, 1999b and references therein).

Significant improvements in technological innovation over the past several years have brought the hardware to compensate in real-time for telescope image degradation induced by the atmospheric turbulence that distorts the characteristics of light traveling through it. The limitation is due to warping of iso-phase surfaces and intensity variation across the wavefront, thereby, distorting the shapes of the wavefront (Fried, 1966). The blurring suffered by such images is modeled as convolution with the point spread function (PSF). Wavefront sensing and adaptive optics (AO) are based on this hardware oriented correction (Babcock, 1953, Rousset et al., 1990).

Success in synthesizing images obtained from a pair of independent telescopes on a North-South baseline configuration (Labeyrie, 1975, Labeyrie et al., 1986, Shao et al., 1988), impelled astronomers to venture towards ground-based very large arrays (Davis et al., 1992). Potentials for progress in the direction of developing large interferometric arrays of telescopes (Labeyrie, 1996) are expected to provide images, spectra of quasar host galaxies, exo-planets that may be associated with stars outside the solar system (Labeyrie, 1995, 1998a, 1998b). Plans are also on to put an interferometer of a similar kind on the surface of the moon at the fall of this century. The technique of developing long baseline Fizeau-type interferometer for lunar operation consisting of 20 to 27 off-axis parabolic segments carried by robotic hexapodes that are movable during observing run has been suggested by Arnold et al., (1996). In a very recent article, Saha (1999a) has discussed at length about the interferometric techniques, that include the basic features of the working long baseline interferometers (LBI) with two or more optical telescopes. This review focuses on the current activities of the various groups across the globe to develop new ground-based, as well as space-borne interferometers in the optical domain, data processing techniques being adapted at the working LBIs; an account of historical development of high resolution astronomy is enunciated for the benefit of the readers as well. Some of the important results obtained with the new interferometers are also highlighted.

2. Historical development of ground-based interferometry

High angular resolution of an stellar object is an important aspect which astronomers are aspiring for. Ever since Fizeau (1868) had suggested to install a screen with two holes on top of the telescope that produce Young's fringes at its focal plane as the fringes remain visible in presence of seeing, several attempts have been made with moderate sized telescopes to measure stellar diameters. Stéphan (1874) tried to resolve Sirius by using several masks with hole separation up to 65 cm on the 80 cm telescope of Observatoire de Marseille (France). No fringe contrast change was noticed and, therefore, only a maximum diameter of Sirius was deduced. One of the first significant results was the measurement of diameter of the satellites of Jupiter with a Fizeau interferometer on top of the Yerkes refractor by Michelson (1891). With the 100 inch telescope at Mt. Wilson (Anderson, 1920), the angular separation of spectroscopic binary star Capella was also determined.

To overcome the restrictions of the baseline, Michelson (1920) constructed the stellar interferometer equipped with 4 flat mirrors to fold the beams by installing a 7 m steel beam on top of the afore-mentioned 100 inch telescope; the supergiant star α Orionis were resolved (Michelson and Pease, 1921). Due to the various difficulties, viz., (i) effect of atmospheric turbulence, (ii) variations of refractive index above small sub-apertures of the interferometer, and (iii) mechanical instability, the project was abandoned.

2.1. Intensity interferometry

The field of optical interferometry lay dormant until it was revitalized by the development of intensity interferometry (Brown and Twiss, 1958). Success in completing the intensity interferometer at radio wavelengths (Brown et al., 1952), in which the signals at the antennae are detected separately and the angular diameter of the source is obtained by measuring correlation of the intensity fluctuations of the signals as a function of antenna separation, Brown and Twiss (1958) demonstrated its potential at optical wavelengths by measuring the angular diameter of Sirius. Subsequent development of this interferometer with a pair of 6.5 meter light collector on a circular railway track spanning 188 meter (Brown et al., 1967), depicted the measurements of 32 southern binary stars with angular resolution limit of 0.5 milliarcseconds (Brown, 1974). The project was abandoned due to lack of photons beyond 2.5 magnitude stars.

2.2. Single aperture interferometry

Meanwhile, Labeyrie (1970) had invented speckle interferometric technique that retrieves the diffraction-limited information of an object. The diffraction-limited resolution of celestial objects viewed through the Earth's turbulent atmosphere could be achieved with the large optical telescope, by post detection processing of a large data set of short-exposure images using Fourier-domain methods. Certain specialized moments of the Fourier transform of a short-exposure image contain diffraction-limited information about the object of interest. Owing to the turbulent phenomena associated with heat flow and winds in the atmosphere, the density of air fluctuates in space and time. The inhomogeneities of the refractive index of the air can have devastating effect on the resolution achieved by any large telescope. The disturbance takes the form of distortion of the shape of the wavefront and variations of the intensity across the wavefront. Due to the motion and temperature fluctuations in the air above the telescope aperture, inhomogeneities in the refractive index develop. These inhomogeneities have the effect of breaking the aperture into cells with different values of refractive index that are moved by the wind across the telescope aperture.

The power spectral density of refractive index fluctuations caused by the atmospheric turbulence follows a power law with large eddies having greater power (Tatarski, 1967). A plane wave propagating through the atmosphere of Earth is distorted by refractive index variation in the atmosphere (troposphere); it suffers phase fluctuations and reaches the entrance pupil of with patches of random excursions in phase (Fried, 1966). Therefore, the image of the star in the focal plane of a telescope is larger than its Airy disk (theoretical size $1.22\lambda/D$ is known as Rayleigh limit or diffraction limit, where, D is the diameter of the telescope). The size is equivalent to the atmospheric point spread function (point spread function is a modulus square of the Fourier transform of the aperture function). The resolution at the image plane of the telescope is determined by the width of the PSF which is of the order of $(1.22\lambda/r_0)$, where, λ is a wavelength of light and r_0 is the average size of the turbulence cell, which is of the order of 10 cm. The statistical properties of speckle pattern depend both on the coherence of the incident light and the properties of random medium. Mathematically, speckles are simply the result of adding many sine functions having different, random characteristics. Since the positive and negative values cannot cancel out everywhere, adding an infinite number of such sine functions would result in a function with 100 % constructed oscillations. Further details about the technique, way of recording speckles of any astronomical objects, image processing can be found in the most recent article by Saha (1999a, 1999b).

The afore-mentioned technique has been successful in obtaining spectacular results of a wide range of objects; a glimpse of such studies can be found in a recent review by Saha (1999a and references therein). Studies of the morphology of stellar atmospheres, the circumstellar environment of nova or supernova, YPN, long period variables (LPV), rapid variability of AGNs etc., are of paramount importance in astrophysics. Details of the structure of a wide range of stellar objects at scales of $0.015''$ - $0.03''$ are routinely observed. The physical properties of red dwarfs in the vicinity of sun can also be looked into; some dwarfs may often be close binaries. Speckle interferometric technique has been extended to IR domain too. With the photon counting detector system (Saha, 1999a and references therein) which is an essential tool in the application of optical interferometric imaging that allows the accurate photon centroiding, as well as provides dynamic range needed for measurements of source characteristics, one can record the specklegrams of the object of faintest limiting magnitude. Further benefits have been witnessed when the atmospherically degraded images of these objects are applied to image restoration techniques (Liu and Lohmann, 1973, Rhodes and Goodman, 1973, Knox and Thomson, 1974, Lynds et al., 1976, Weigelt, 1977, Lohmann et al., 1983, Ayers and Dainty, 1988) for obtaining Fourier phase. Mapping the finer features of such objects would produce qualitative scientific results.

Development of various interferometric techniques, namely, (i) speckle spectroscopy (Grieger and Weigelt, 1992), (ii) speckle polarimetry (Falcke et al., 1996), (iii) pupil plane interferometry (Roddier and Roddier, 1988), (iv) Closure-phase method (Baldwin et al., 1986), (v) aperture synthesis using both partial redundant and non-redundant masking (Haniff et al., 1987, 1989, Nakajima et al., 1989, Busher et al., 1990, Bedding et al., 1992, 1994, Bedding, 1999), (vi) differential speckle interferometry (Petrov et al., 1986) too contribute in obtaining new results. Adaptive optics system introduces controllable counter wavefront distortion which both spatially and temporally follows that of the atmosphere. Adaptive optical systems may become standard tool for the new generation large telescopes. A considerable amount of new results have already been published. Detailed technique and the results can be seen in the recent reviews (Léna, 1997, Léna and Lai, 1999a, 1999b, Saha, 1999a).

2.3. Amplitude and phase interferometry

Subsequently, Labeyrie (1975) had developed a long baseline optical interferometer – Interféromètre à Deux Télescopes (I2T) – with a pair of 25 cm telescopes at Observatoire de Calern, France, exploiting the concept of merging speckles from both the telescopes. In other words, the fringed speckle can be visualized when a speckle from one telescope is merged with the speckle from the other. His design combines features of the Michelson and of the radio interferometers. The use of independent telescopes increases the resolving capabilities. In this case, Coudé beams from both the telescopes arrive at central station and recombines them. Apart from the first measurements for a number of giant stars (Labeyrie, 1985), this interferometer also determined the effective temperatures of giant stars (Faucherre et al., 1983). In addition, resolving the gas envelope of the Be star γ Cassiopeiae in the Hα line (Thom et al., 1986) has a major achievement from I2T. In the infrared, diameters of cool bright giants and their effective temperature at 2.2 μm (DiBenedetto and Rabbia, 1987) have also been measured.

Following the success of its operation, Labeyrie (1978) undertook a project of building large interferometer known as Grand Interféromètre à Deux (two) Télescopes (GI2T) at the same observatory. This interferometer comprises of two 1.5 meter spherical telescopes on a North-South baseline, which are movable on a railway track (Labeyrie et al., 1986). The first scientific result came out of this interferometer in 1989 (Mourard et al., 1989) that had resolved the rotating envelope of hot star γ Cassiopeiae. This object has been the favorite target to the GI2T (Stee et al., 1995, 1998). The emerging results on β Lyrae, δ Cep (new and accurate distance estimate), P Cyg (the first discovery of an asymmetry in its wind) and ζ Tau (the first evidence for a one-armed oscillation in a Be star equatorial disk) are the most spectacular results from the GI2T too (Mourard et al., 1997, Harmanec et al., 1996, Vakili et al., 1997, 1998a, 1998b). The technical details of this kind of interferometers can be found in the recent article by Saha (1999a).

There are several long baseline interferometers, viz., (i) Mt. Wilson stellar interferometer, (ii) Sydney University stellar interferometer (SUSI), (iii) Cambridge Optical Aperture Synthesis Telescope (COAST), (iv) Infrared Optical Telescope Array (IOTA) are in operation. The technical details of these interferometers, as well as the results obtained so far can be found in the review article by Saha (1999a). However, a few salient objectives and programmes of these are reported in brief.

Measurements of precise stellar positions and motions of the stars are the major programmes being carried out with the Mark III interferometer at Mt. Wilson (Shao et al., 1990, Hummel, 1994). This set up has also been used to derive the fundamental stellar parameters, like the orbits for spectroscopic, as well as eclipsing binaries (Armstrong et al., 1992a, 1992b, Pan et al., 1992, Shao and Colavita, 1994), structure of circumstellar shells (Bester et al., 1991) etc.

The interferometers, namely, COAST, SUSI, IOTA etc., are relatively new. The expansion of a few of them are in progress. Nevertheless, they have produced several interesting results. Among the notable ones with COAST, mapping of the double-lined spectroscopic binary α Aurigae, resolving of α Tau are the important ones (Baldwin et al., 1996, 1998); detecting a circularly symmetric data with an unusual flat-topped and limb darkening profile of α Orionis (Burns et al., 1997), variations of the cycle of pulsation of Mira variable R Leonis (Burns et al., 1998) etc., have also been reported. With the SUSI interferometer, Davis et al., (1998, 1999) have determined the diameter of δ CMa with an accuracy of $\pm 1.8\%$. The results with the IOTA interferometer so far reported are from the near IR bands. They are in the form of measuring the angular diameters and effective temperatures of carbon stars (Dyck et al., 1996a), carbon Miras and S types (Van Belle et al., 1997), K and M giants and supergiants (Dyck et al., 1996b, 1998, Perrin et al., 1998), Mira variables (Van Belle et al., 1996), and cool giant stars (Dyck et al., 1995).

3. On-going ground-based interferometric projects

In view of the growing importance of high angular resolution interferometry, several projects of developing LBIs are in progress. Since the technical details of the well established interferometers have been already described in the recent article by Saha (1999a), the salient features of some of the on-going interferometric projects are enumerated.

3.1. Palomar testbed interferometer (PTI)

The Palomar testbed interferometer (PTI), is an infrared phase-tracking interferometer in operation situated at Palomar Observatory, California; it was developed by the Jet Propulsion Laboratory and California Institute of Technology for NASA as a test-bench for the Keck interferometer. The main thrust of this interferometer is to develop techniques and methodologies for doing narrow angle astrometry for the purpose of detecting extra-solar planets (Wallace et al., 1998) that measures the wobble in the position of a star caused by the transverse component of a companion's motion.

Three 40 cm siderostats (steerable flat mirrors for sending starlight in a fixed direction) coupled to beam compressors (reducing the beam diameter) can be used pairwise to provide baselines up to 110 m (Colavita et al., 1999). This interferometer tracks the white light fringes using an array detector at 2.2 μm (K band) and active delay-lines with a range of ± 38 m. Among others, the notable feature of this interferometer is that of implementation of a dual-star astrometric ability; observation of fringes from 2 close stars simultaneously for phase referencing and narrow-angle astrometry. An end-to-end heterodyne laser metrology system is used to measure the optical path length of the starlight (Wallace et al., 1998). They also claimed better performances after the recent upgradations of PTI, viz., a single mode fiber for spatial filtering, vacuum pipes to relay the beams, accelerometers on the siderostat mirror etc.

Malbet et al., (1998) have resolved the young stellar object FU Orionis using the said interferometer in the near infrared with a projected resolution better than 2 AU. Observations of the young binary stars, ι Peg have been also conducted by Pan et al., (1996) with this interferometer. They have determined its visual orbit with separation of 1 mas in R. A., having a circular orbit with a radii of 9.4 mas. Measurements of diameters and effective temperatures of G, K, and M giants and supergiants have been reported recently by Van Belle et al., (1999). The visual orbit for the spectroscopic binary ι Peg with interferometric visibility data recoded by PTI has also been derived (Boden et al., 1999).

3.2. Navy prototype optical interferometer (NPOI)

The astrometric array of NPOI, a joint project of the US Naval Research laboratory and the US Naval Observatory is designed to measure positions with precision comparable to that of Hipparcos (1997). This interferometer is located at the Lowell Observatory, Arizona and is capable of maintaining accuracy of the positions of the brightest Hipparcos stars while improving the precision of their proper motions. The anticipated wide-angle astrometric precision of the NPOI is about ~2 mas. (Armstrong et al., 1998). Since the high precision astrometry is an important aspect to astronomy that helps in establishing cosmic distance scale; measurements of proper motion can confirm stars as members of cluster (known distance) that may elucidate the dynamics of the Galaxy. NPOI plans to measure the positions of some radio stars that would help in matching radio sources with their optical counterparts.

This interferometer includes sub-arrays for imaging and for astrometry and is developed at Y-shaped (Very Large Array-like) baseline configuration. The light beams are passed through vacuum pipes to the central laboratory. For astrometric mode, 4 fixed siderostats (0.4 m diameter) are used with the baselines extendable from 19 m to 38 m (Armstrong et al., 1998). The shared back and covers 450-850 nm in 32 channels. The other notable features are the delay system, active group-delay fringe tracking etc. The astrometric sub-array has a laser metrology system to measure the motions of the siderostats with respect to one another and to the bedrock. While for imaging mode, 6 transportable siderostats (0.12 m diameter) are used with the baselines from 2 m to 432 m. Three siderostat positions are kept with equal space for each arm of the Y. Coherence of imaging configuration is maintained by phase bootstrapping (see section 4.1). Observations in visible spectrum with 3-elements have been carried out using avalanche photo-diode as detector (Hummel et al., 1998). The dynamic range in the best of the NPOI images exceeds 100:1 (Armstrong et al., 1998).

A few examples of science with NPOI can be read from the following results. Pauls et al., (1998) have measured the limb darkened angular diameters of late-type giant stars using the said interferometer with three optical elements; measurement of non-zero closure phase has been performed on a single star. Hajian et al., (1998) have also observed the limb darkened diameters of two K giants, α Arietis and α Cassiopeiae with 20 spectral channels covering 520-850 nm. They were able to extend the spatial frequency coverage beyond the first zero of the stellar visibility function for these stars. Hummel et al., (1998) have determined the orbital parameters of two spectroscopic binaries, ζ Ursae Majoris (Mizar A), η Pegasi (Matar) and derived masses and luminosities based on the data obtained with interferometer; published radial velocities and Hipparcos trigonometrical parallaxes were used for the analysis.

3.3. Keck interferometer

The development of Keck interferometer consisting of 2 × 10 m apertures (main telescopes) with a fixed baseline of 85 m is in progress: the expected resolution of this is of the order of 5 mas at 2.2 μm. The baselines available with outrigger telescopes (4 × 1.8 m) will be between 25 m to 140 m (fixed baselines). For imaging the main telescope would be used with outriggers (Colavita et al., 1998). This project is funded by NASA and is being carried out by Jet Propulsion Laboratory (JPL) and California Association for Research in Astronomy (CARA). This large interferometer is located at Mauna Kea Observatory, Hawaii. It will combine phased pupils provided by adaptive optics for the main telescopes (up to V=9, 39 mas FWHM, Strehl ratio=30%) and fast tip/tilt correction on the outriggers. Beam recombination will be carried out by 5 two-way combiners at 1.5-2.4 μm for fringe tracking, astrometry, and imaging. Project for a 10 μm nulling-combiner for exo-zodiacal disk characterization is also undertaken.

The astrometric accuracy is expected to be of the order of 20 to 30 μas/$\sqrt{\text{hour}}$. With the main telescopes, observations for searching Jovian planets, as well as for characterizing the exo-zodiacal disks may commence by 2001 and with the addition of the outriggers, astrometric observation will be carried out by 2003.

3.4. Very large telescope interferometer (VLTI)

The VLTI, built by the European Southern Observatory and located at Cerro Paranal, Chile, will be a versatile facility consisting of four 8 m fixed telescopes ("unit telescopes") and three 1.8 m mobile auxiliary telescopes which can be installed on any of the 30 stations built on the ground. The maximum baseline of VLTI is 200 m. Siderostats for first tests could be used as well (Derie et al., 2000). Coudé beams from these apertures are sent through delay-lines operating in rooms at atmospheric pressure but at a thoroughly controlled temperature in order to avoid turbulence. The beams reach an optical switchyard to be directed to one of the four expected recombiners: VINCI (Kervella et al., 2000), MIDI (Leinert and Graser, 1998), AMBER (Petrov et al., 2000) or PRIMA (Quirrenbach et al., 1998).

VINCI (VLT INterferometer Commissioning Instrument) will be a single-mode fiber recombiner operating at 2.2 μm like FLUOR (see 3.7) and is intended to be used for debugging the upstream sub-systems of VLTI. MIDI (MID-Infrared) will be a beamsplitter-based recombiner that will be used for observations at 10 μm. AMBER (Astronomical Multiple BEam Recombiner) has been designed for observations between 1 μm and

2.5 μm. It will be able to perform recombination of three beams in order to use closure-phase techniques. PRIMA (Phase-Reference Imaging and Microarcsecond Astrometry) is a recombiner dedicated to narrow-angle astrometry (see 6.1). It should be able to reach a 10 μas resolution.

By the end of 1999, two unit telescopes were operating and the primary mirror has been installed on the third one. First fringes of the VLTI with two siderostats and VINCI are scheduled for the end of 2000. All the remaining combiners are scheduled to work either with the unit or the auxiliary telescopes by 2005.

3.5. Center for high angular resolution astronomy (CHARA) array

The Center for High Angular Resolution Astronomy (CHARA), Georgia State University, is currently building an interferometric array at Mt. Wilson, California, USA; it comprises six fixed 1 m telescopes arranged in a Y-shaped configuration with a maximum baseline of ~350 m that would operate at optical and IR wave band (McAlister et al., 1998) with a limiting resolution of 0.2 mas. The main objective of this project is to measure the diameters, distances, masses and luminosities of stars, as well as to image features, viz., spots and flares on their surfaces. The aim of this project range from detecting other planetary systems to imaging the black hole driven central engines of quasars and active galaxies.

Light from the telescopes is sent through vacuum pipes to the centrally located Beam synthesis facility, a L-shaped long building (McAlister et al., 1994) that houses the optical path length equalizer (OPLE) and the beam combination laboratory (BCL). Constructions of piers for the five telescopes (McAlister et al., 1998) have been completed. Optical delay line carts and their metrology, similar versions that are used at NPOI and PTI, and control systems, are being developed at JPL, USA. The first fringes in K band from a star have been acquired with two telescopes of CHARA by the end of 1999. The other baselines and the visible spectrum recombiner should be operational in the next few years.

3.6. Grand interféromètre à deux télescopes (GI2T) current status

The detailed description of GI2T is available in a recent article by Saha (1999a). This interferometer has recently been upgraded with a new recombiner named REGAIN (REcombineur pour GrAnd Interféromètre). This recombiner, able to operate with three telescopes (Mourard et al., 1998) has the following features.

The 76 mm Coudé beams coming from the telescopes are first compressed to 5 mm in order to stabilize the pupil image in a fixed plane. Then, field rotators consisting of four plane mirrors are used for each beam to compensate the polarization difference affecting the visibility measured (Rousselet-Perraut et al., 1996). The different chromatic dispersion between the two beams (due to operation at atmospheric pressure) is compensated by using for each beam two prisms which can slide on their hypotenuse, forming therefore a plate with adjustable thickness. This thickness is modified every 4 minutes, following the variation of the altitude of the observed object. Figure 1 depicts the process performed by an arm of the REGAIN table prior to recombination. Unlike the previous recombiner which had to move to track fringes, REGAIN uses a delay-line named LAROCA (Ligne A Retard de l'Observatoire de la Côte-d'Azur) featuring a cat's eye reflector with a variable curvature mirror. An adaptive optics for the 1.5 m telescopes of GI2T is in development (Vérinaud et al., 1998).

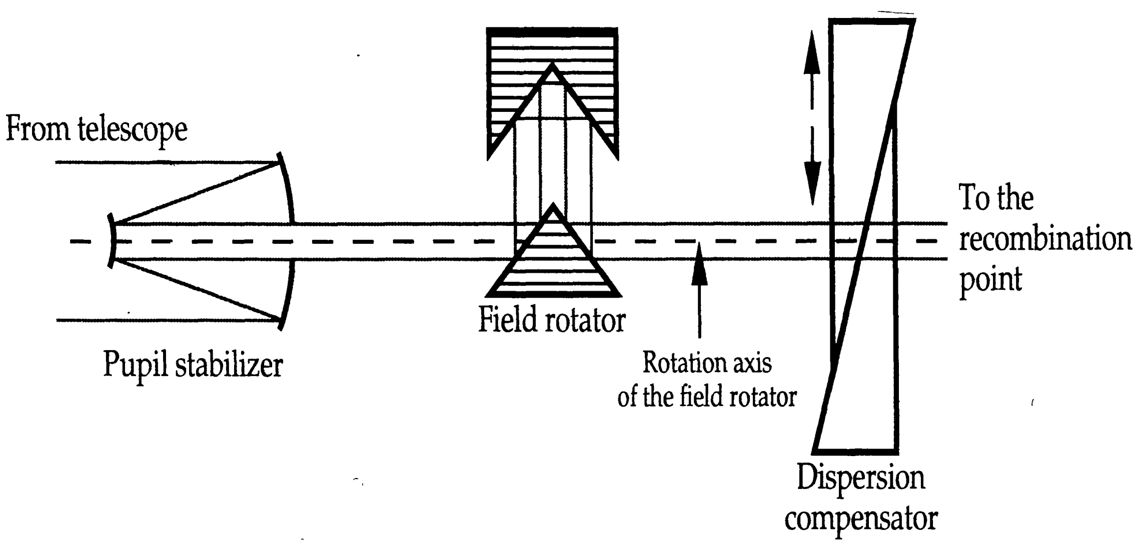

Figure 1. Optical processing of a beam from one telescope of GI2T by the REGAIN recombiner.

The focal instrument of GI2T/REGAIN will be a spectrometer working either in dispersed fringes mode or in Courtès mode. In dispersed fringes (see 4.1), the spectral range is 480 nm to 750 nm and the spectral resolution can reach $R = 30,000$. Separated recombination of two orthogonal polarizations will be possible. The detectors used will be two CP40 photon cameras. The Courtès mode consists in forming images at different wavelengths of speckles with fringes given by the recombination. The spectrometer of REGAIN in Courtès mode will be able to give 16 images at the same time.

However, first fringes (at 2.2 μm) with GI2T/REGAIN have already been acquired in August 1999 (Weigelt et al., 2000) thanks to a different slit spectrometer and a PICNIC infrared camera built by the Max-Planck-Institute für Radioastronomie (Bonn, Germany).

3.7. Infrared optical telescope array (IOTA) current status

A description of IOTA has already been presented in this journal (Saha, 1999a). IOTA has recently been upgraded (Traub et al. 2000) with a supplementary optical path delaying system (consisting of a long-travel delay-line fixed while observing and a short-travel delay-line tracking the star), a new control system for the long delay-lines and new high-precision secondary mirror holders for the telescopes. The third collector similar to the two already existing (a 45 cm siderostat and a fixed Mersenne telescope compressing the beam by 10) will soon be operational. Identical reflections are applied to the beams from the collectors to the recombiner in order to avoid any loss of fringe contrast due to different polarization states between the two beams at the recombination point. Figure 2 depicts the overview of IOTA interferometer.

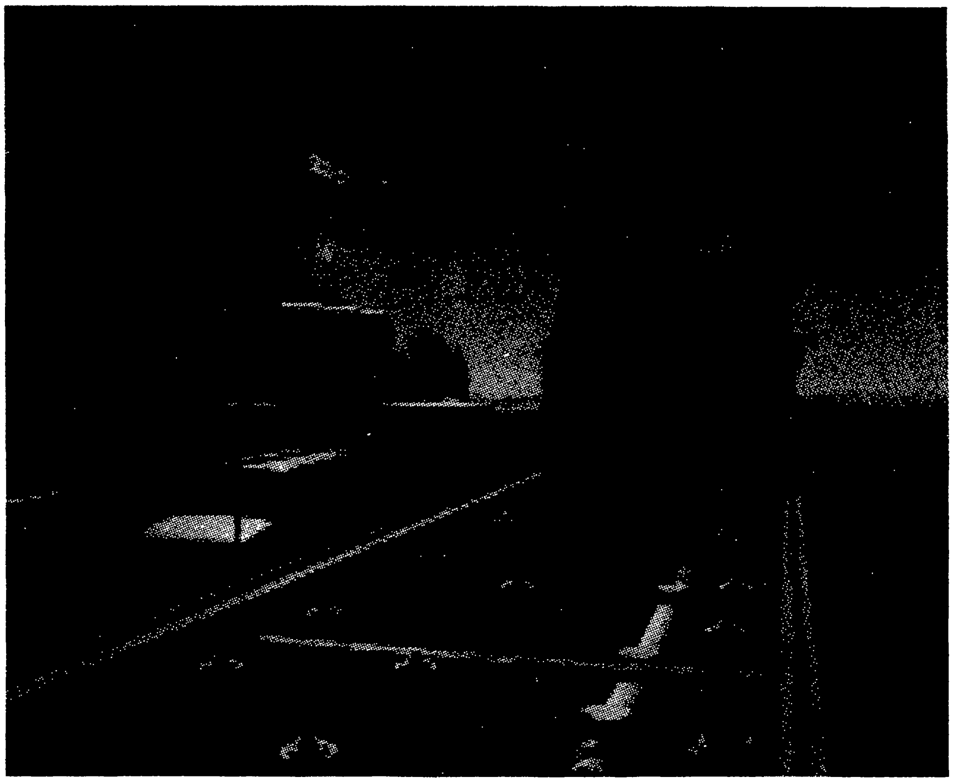

Figure 2. Overview of IOTA interferometer.

The focal instrumentation consists of two infrared recombiners. The first one uses a classical beamsplitter (see 4.1). The two recombined beams are focused on two pixels of a NICMOS III infrared camera (Millan-Gabet et al., 1999). This camera is able to read up to ten fringe frames per second. Each fringe frame, containing 256 samples, is made by scanning the optical path difference between the two beams with a mirror mounted on a 60-micron stroke piezo-electric transducer (PZT). Last scientific results obtained with this instrument include environment characterization of Herbig AeBe stars (Millan-Gabet et al., 1998) and dust shell diameter measurement of CI Cam (Traub et al., 1998).

The second recombiner named FLUOR (Fiber-Linked Unit for Optical Recombination, (Coudé du Foresto and Ridgway, 1992) consists of single-mode fiber optics interfering beams (Shaklan and Roddier, 1987). These fibers have been designed to propagate infrared light at K band (2.2 μm) in TEM mode only, like a coaxial cable. Therefore, only plane waves perpendicular to the axis of the fiber may propagate over long distances. Concretely, this results in a "spatial filtering", smoothing the wavefronts that have been corrugated by atmospheric turbulence. Figure 3 depicts the principle of wavefront smoothing by spatial filtering with a pinhole and with a single-mode fiber. The advantage of such a technique for interferometry is a reduction of the uncertainty on the measured visibility.

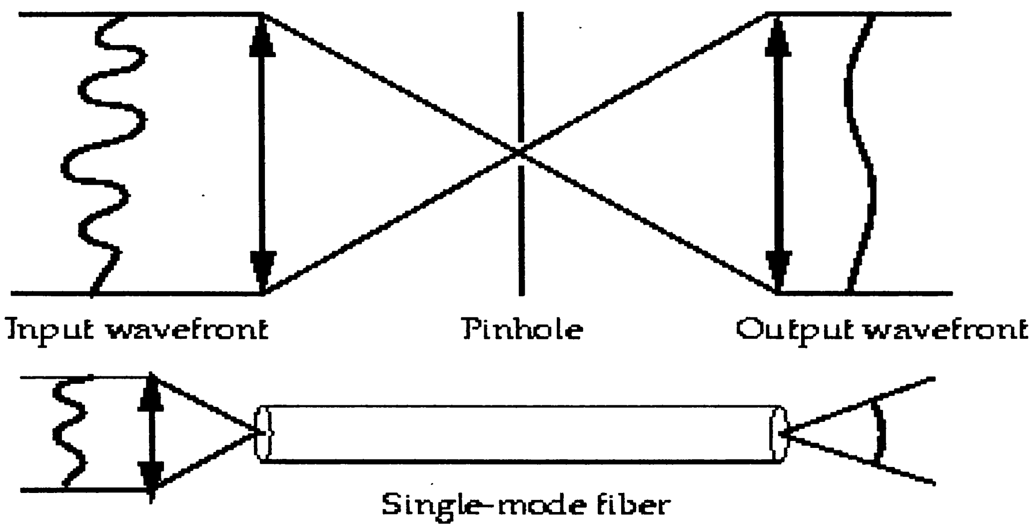

Figure 3. Principle of wavefront smoothing by spatial filtering with a pinhole and with a single-mode fiber.

Drawbacks of spatial filtering are a loss of optical coupling efficiency and larger photometric variations due to the turbulence. The FLUOR experiment was originally set up at the McMath solar tower of the Kitt-Peak National Observatory (Arizona), with a 5 m baseline. It has been installed at IOTA since 1994. The current FLUOR bench use a 180-micron stroke PZT for scanning the fringes. The detector used is the NICMOS III of IOTA. Four pixels are read (two for the interferometric fiber outputs, two for the photometric fiber outputs). Accurate diameter measurements of Mira variable stars (Perrin, 1999) and cepheids (Kervella et al., 1999), effective temperature measurements of giant stars (Perrin et al., 1998), have recently been done with FLUOR on IOTA. Figure 4 depicts the schematic of the FLUOR recombiner.

Attempts to observe with single-mode fibers at longer wavelengths at IOTA (TISIS experiment) have been done in L band (3.5 μm) by Menesson et al., (1999), and in M band (5 μm) in March 1999 (Menesson et al., 2000). However, the thermal background of the instrument and the presence of an atmospheric H_2O absorption line in M band barred fringe acquisition.

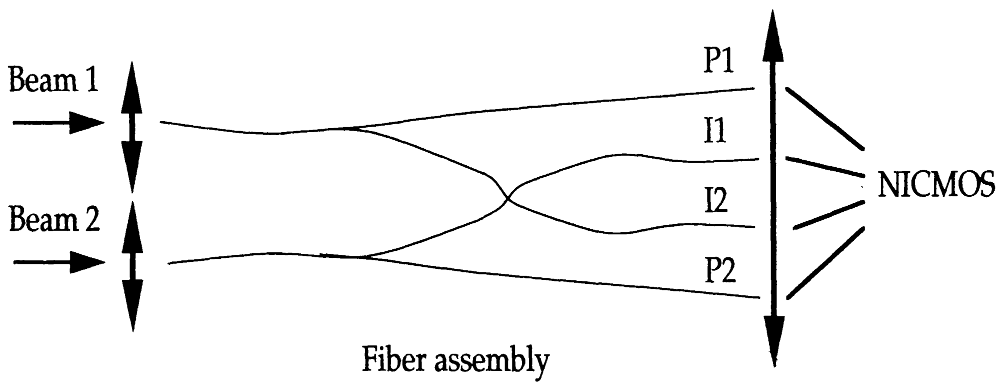

Figure 4. Schematic of the FLUOR recombiner. P1 and P2 are the photometric output fibers. I1 and I2 are the interferometric output fibers. These outputs are imaged by a lens on a NICMOS infrared array detector.

3.8. Optical very large array (OVLA)

The OVLA is a project that was initiated about 10 years ago by A. Labeyrie. It is proposed to build an interferometer using innovative concepts. First, the collectors will be radically different from what has already been imagined. Each telescope structure (Dejonghe et al., 1998) is a 2.8 m diameter fiberglass sphere which may be oriented in any direction thanks to three motors featuring specially designed "barrel-caster" cabestans, mounted on their shafts. The sphere rests on these three barrel-casters: when one of them is steering the sphere, no friction occurs from the other two. The mirror of each telescope (1.5 m diameter with f/1.7) is made of ordinary window glass. It is 24 mm thick and weights 180 kg. An active optics is, therefore, required in order to get high-quality wavefronts for interferometric purpose: the mirror rests on three hard points and 29 actuators able to accurately correct its shape. Correction of the spherical aberration may be done by applying an electric current through the mirror coating between two chosen points of the edge, thus heating the top side of the mirror to compensate the noticed temperature difference with the bottom side (about 0.5°C). A secondary mirror makes the beam afocal and compressed, a third steerable flat mirror sends this beam out through a slit located on the sphere. A motorized shutter can partially close this slit when a barrel-caster and the slit are in coincidence. It has been projected to mount the sphere and its motorization on a six-leg robot (hexapode) able to move on the ground while fringes are acquired (in order to compensate the OPD between beams). Due to its original features, an OVLA telescope requires a significant amount of electronics and a control system (Lardière et al., 1998) that can actuate in real-time motors, actuators, shutter, hexapode. The first OVLA telescope has been tested in October 1999 (Arnold et al., 2000): the point spread function of the optics was 4" FWHM. Improvements of the image quality by a better control of the actuators remains, that can produce diffraction-limited images. Once this is done, the OVLA might be used as the third telescope of the

GI2T interferometer making it "GI3T". Figure 5 depicts the first operating telescope of proposed OVLA.

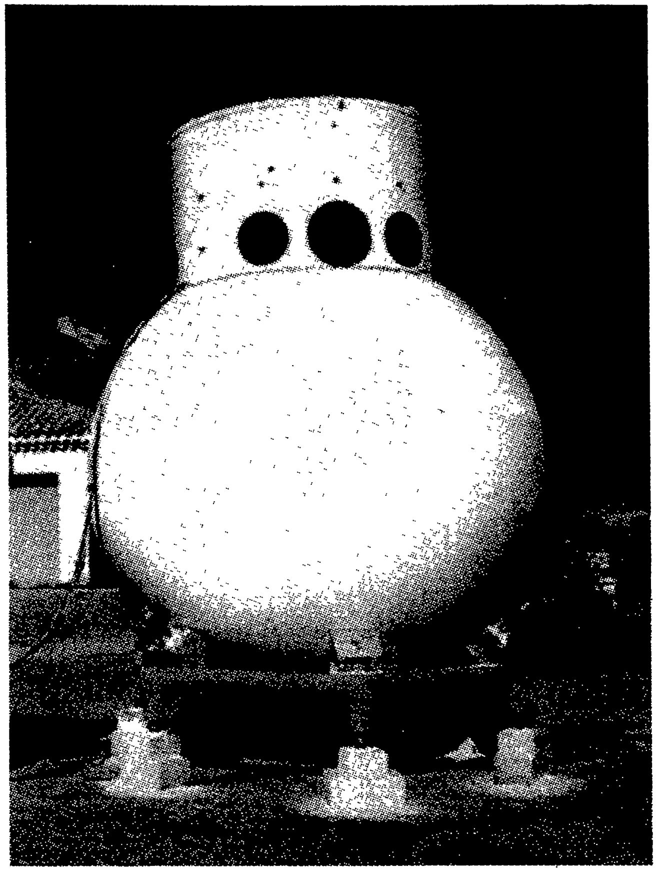

Figure 5. One of the telescope of proposed OVLA (Courtesy: O. Lardière).

The OVLA has actually been thought for different possible aperture diameters including 12 to 25 m (Labeyrie, 1998c). A new telescope structure has been imagined for this class of very large collectors: the "cage telescope", in which the sphere is replaced with an icosahedral truss steerable by a different mechanical system. There are several options for the configuration of the OVLA interferometer featuring 27 apertures (like the Very Large Array radio-interferometer). The first one is to build a Fizeau interferometer, i.e. a fragmented giant telescope. Each telescope is shaped as it was a segment of the paraboloid mirror of the synthesized giant telescope. The array is arranged on the ground to form an ellipse. Images are then directly obtained at a recombination station located at a focus of the ellipse. This Fizeau configuration was thought for LOVLI (Lunar Optical Very Large Interferometer), the moon-based version of OVLA. However, controlling the particular shape of each telescope will be very difficult. A recent new concept of interferometric recombination, especially imagined for OVLA, is called "densified pupil"

(Labeyrie, 1996). In Fizeau mode, the ratio aperture diameter/separation is constant from light collection to recombination in the image plane (homothetic pupil). In Michelson mode, this ratio is not constant since the collimated beams have the same diameter from the output of the telescope to the recombination lens. The distance between pupils is equal to the baseline at the collection and to a much smaller value just before the recombining lens. The disadvantage of the Michelson mode is a very narrow field of view compared to the Fizeau's. However, a densified pupil interferometer ("extreme Michelson mode"), where, in the recombination plane, the distance between two pupils corresponding to two telescopes is minimized to become about equal to their diameter, may be very interesting to get direct images without using the heavy procedure of aperture synthesis (visibility measurement, phase calibration, Fourier synthesis...). It can be demonstrated that the definition (i.e. number of pixels of the image) of a densified pupil interferometer is equal to the square of its number of apertures. One difficulty is cophasing all the beams. Since 27 ($= 3^3$) telescopes are expected, the cophasing of the whole array may be done hierarchically (Pedretti and Labeyrie, 1999) by cophasing triplets of beams (yielding a honeycomb pattern in the image plane), then triplets of triplets, etc... The limitation of the cophasing procedure by the photon noise would not be very important. According to numerical simulations, the expected limiting magnitude of the densified pupil OVLA is 8.3 if 10 cm apertures are used and 20 for 10 m apertures.

3.9. Mitaka optical infrared arrays (MIRA)

The MIRA project (a collaboration between the University of Tokyo and the National Astronomical Observatory of Japan) does not consist of one but several interferometers built one-by-one, each instrument being an upgrade of the previous one. The first of the series was MIRA-I (Machida et al., 1998). It had 25 cm siderostats and a 4 m baseline. The fringe detector was designed for 800 nm wavelength. Its successor, MIRA-I.2 (Sato et al., 1998) has the same baseline and slightly larger siderostats (30 cm). It features the equipment encountered on many operating interferometers: beam compressors (yielding 30 mm beams), delay-line operating in vacuum, tip-tilt correction system and laser metrology. MIRA-I and MIRA-I.2 are instruments specially designed for practicing interferometry and testing devices. The experience acquired from these interferometers will be useful for building larger interferometers of the MIRA project like MIRA-II, MIRA-SG and MIRA-III, which will be instruments for astrophysical research.

4. Data acquisition and processing in optical interferometry

Operating a long-baseline interferometer (i.e. finding fringes, measuring their visibility, interpreting the result) is a long and difficult process. First, a correct determination of the baseline vector must be established. Once this has been done, one knows, for a given object to observe, how to set the position of the optical delay-line to get fringes within, usually, a few hundred micron interval around the expected null-OPD point. Then, optics must be adjusted to avoid various aberrations and vignetting, which may be difficult to avoid when light is fed through long and narrow pipes. Then, fringes are searched by adjusting the delay-line position. However, once they are found, mechanical constraints on the instrument, errors on the pointing model, thermal drifts, various vibrations and atmospheric turbulence make the null-OPD point changing. The position of the delay-line (or any other delaying device in the optical path) must be adjusted in order to keep the fringes within the "observation window": usually, the error on the OPD must be less than the coherence length defined by:

$$L_c = \frac{\bar{\lambda}^2}{\Delta\lambda}, \tag{1}$$

where $\bar{\lambda}$ is the mean wavelength observed and $\Delta\lambda$ is the spectral interval. This real-time control is called "fringe-tracking".

When enough fringe patterns have been recorded, the visibility may be extracted. Then, a set of measured visibilities obtained (i.e. samples in the Fourier plane (u, v) corresponding to the image) allows to partially reconstruct the high-angular resolution image of the observed object.

4.1. Fringe acquisition and tracking

For visible spectrum, three possible set-ups for fringe acquisition exist. In the first one (white fringes), the OPD is temporally modulated by a sawtooth signal, using a fast and short-travel delaying device (usually, a reflector mounted on a PZT). The intensity of the recombined beams describes, therefore, over the time a fringe pattern that is recorded by one or several mono-pixel detectors (photo-multipliers, avalanche photo-diodes, InSb photometers). Natural OPD drift due to the Earth-rotation can also be used for acquiring fringes, as it was done by the SOIRDÉTÉ interferometer (Rabbia et al., 1990). The second method (channeled spectrum) consists of imaging the dispersed recombined beam on a linear detector (CCD or photon-counting camera). In the third one (dispersed fringes), beams are dispersed prior to be recombined. Unlike the two previous techniques, recombination is not done by overlapping the beams, but by focusing them with a common lens, like in the original Michelson stellar interferometer. The detector used is a 2-D photon-counting camera. In infrared, no photon-counting is possible with the current technology. It is, therefore, important to use as less pixels as possible in order to reduce the global readout noise. Hence, the "white" fringes set-up will be preferably used for infrared observations. Figure 6 depicts the various possible set-ups for beam recombination and fringe acquisition.

Techniques to compensate the OPD drift between the two beams of a standard optical interferometer may be classified into two categories: coherencing and cophasing. The aim of coherencing is to keep the OPD within the coherence area of the fringes. Cophasing is a more demanding technique because the OPD must remain much smaller than the

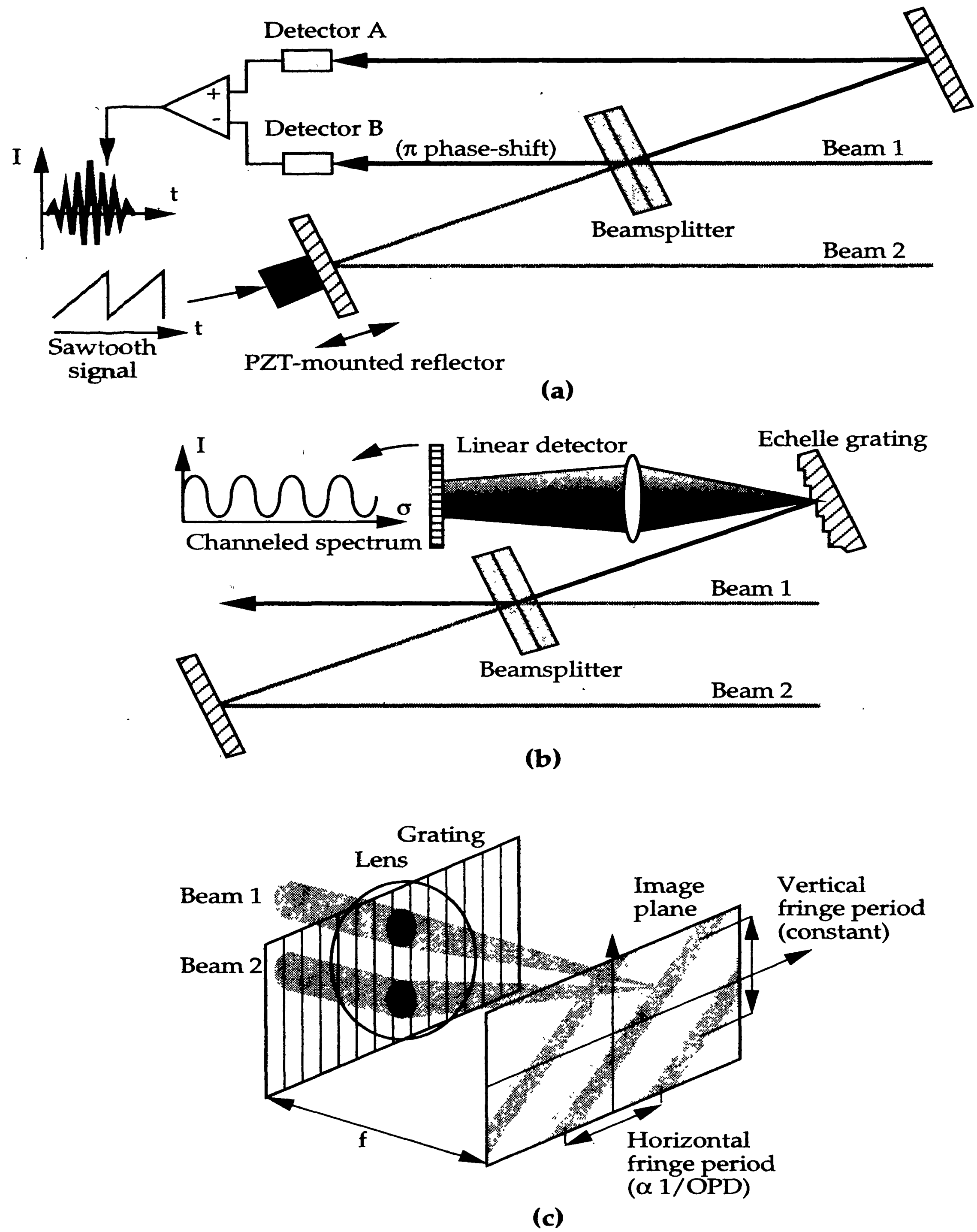

Figure 6. Three possible set-up for beam recombination and fringe acquisition: white fringes (a), channeled spectrum (b), dispersed fringes (c).

wavelength: fast compensation of the OPD variations due to the differential "piston" mode of the turbulence is, therefore, done, in order to "freeze" the fringes.

In white light set-up, the coherencing, as for IOTA (Morel et al., 2000), is done by scanning the OPD while acquiring interferometric signal, and then finding the null-OPD point in the fringe pattern. This yields the OPD correction to apply to the delay-line, at a few Hz servo-loop rate. With a channeled spectrum, the OPD is proportional to the fringe frequency. The method used called "group-delay tracking" (Lawson, 1995), is based on the Fourier transform of each frame acquired. The integration of the moduli of all the computed Fourier Transforms yields a peak whose position is proportional to the OPD. Group-delay tracking has been used on SUSI (Lawson, 1994) and COAST (Lawson, 1998) interferometers. A similar technique (Koechlin et al., 1996) named "real-time active fringe-tracking" (RAFT) has been applied to dispersed fringes on GI2T using a 2-D Fourier Transform. The advantage of RAFT over group-delay tracking is the knowledge of the sign of the OPD to measure and the possibility to be used with apertures larger than r_0, where overlapping wavefronts that have been corrugated by the turbulence would blur the fringes. However, dispersed fringes with large apertures require a complex optical system to rearrange the speckles in the image plane before dispersion and recombination (Bosc, 1988). Both group-delay tracking and RAFT allow a slow servo-loop period (up to a few seconds) by multiplying the coherence length by the number of spectral channels used. It is important to notice that their common use of the Fourier Transform make them optimal in the sense that they yield the same OPD than a maximum likelihood estimator (Morel and Koechlin, 1998).

Cophasing is usually performed with white fringes, using the "synchronous detection" method, as it was used on the Mark III interferometer (Shao and Colavita, 1988): the OPD is quickly scanned over a wavelength. Signal acquired from the detector is then processed in order to yield the phase-shift to compensate and the visibility. This can be done easily (Shao and Staelin, 1977) by integrating signal over four $\lambda/4$ bins, named A, B, C and D. Phase-shift and visibility modulus are then given by:

$$\Delta\varphi = \arctan\left(\frac{B-D}{A-C}\right) \quad ; \quad V = \frac{\pi\sqrt{(A-C)^2+(B-D)^2}}{\sqrt{2}(A+B+C+D)}. \tag{2}$$

The cophasing technique may be compared to adaptive optics, like coherencing with non-white fringes may be compared to active optics. We can notice that a compound method, based on the synchronous detection applied to signals from several spectral channels, has been used on the NPOI interferometer (Benson et al., 1998). Fringe-tracking is usually done from data acquired for scientific purpose (i.e. visibility extraction), in order to not "share" the photons between two instruments. Hence, the fringe signal-to-noise ratio (SNR) is optimal. This fringe SNR is given by the expression (Lawson, 1995):

$$\mathrm{SNR} \propto \frac{NV^2}{\sqrt{1+0.5\times NV^2}}, \tag{3}$$

where N is the number of photons acquired and V the visibility modulus.

However, it may be optimal to have two recombiners, one for visibility measurement, the other one for fringe-tracking. For example, at long baselines, when the expected fringe visibility is too low for tracking, it is possible to use a longer wavelength where the fringe contrast, for a white observed object, is higher. Meanwhile, fringes for computing the visibility are acquired at shorter wavelength than for tracking. Another method where photons are shared is called "bootstrapping". It consists in dividing the baseline into sub-baselines by adding apertures along. Fringe-tracking is performed on each sub-baseline, where the visibility is higher than with the whole baseline. Hence, fringes are tracked on the whole baseline as well. This method is used on the NPOI interferometer (Armstrong et al., 1998). Figure 7 depicts the principle of baseline bootstrapping.

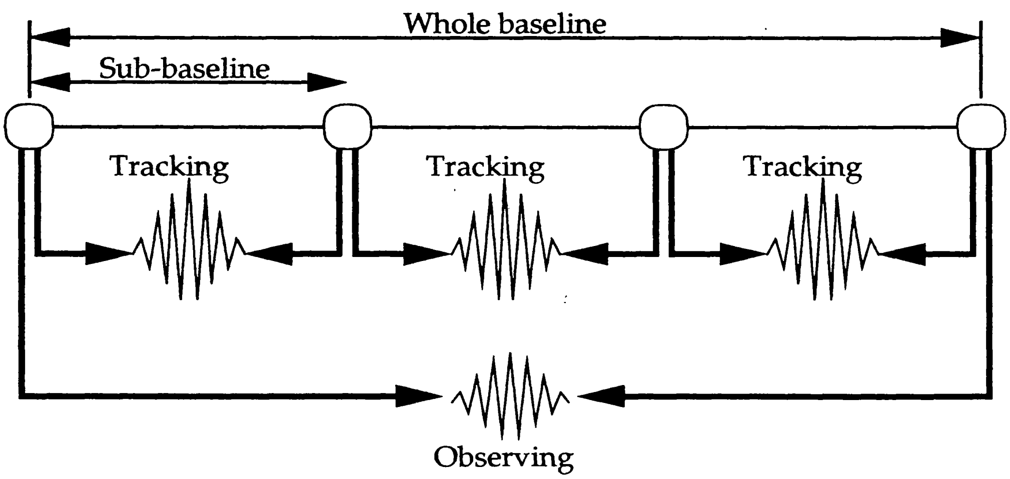

Figure 7. Principle of baseline bootstrapping. Apertures are represented by circles.

Fringe-tracking methods may be enhanced by introduction of *a priori* information, in order to allow observations at fainter V or fainter magnitudes. Gorham (1998) has proposed to improve white light cophasing by filtering data with a function computed to reduce the photon noise. The gain for the tracking limit magnitude, at constant V, is between 0.5 and 0.7. Methods introducing *a priori* information for GDT or RAFT have been imagined as well (Padilla et al., 1998, Morel and Koechlin, 1998).

4.2. Data reduction

The optimal integration time required for measuring a visibility point is a trade-off between the number of photons to collect and the Earth rotation shifting the sampled point in the (u, v) plane. Most of the interferometers use two apertures and are unable to recover the complex visibility. Therefore, the information to extract from a batch of fringes is the modulus of the visibility. Theoretically, using merely the Fourier Transform would give an optimal estimate of the visibility modulus, as demonstrated by Walkup and Goodman (1973). However, white-light fringes obtained from coherencing are flawed by the differential piston that modulates their frequency. Techniques used in radio-interferometry (where wavelengths are much longer), like fitting a sinewave through the fringe data, are, therefore, not suitable. Perrin (1997) has proposed a method to remove the piston from fringes. However, this method requires a high fringe signal-to-noise ratio and may only be applied when fringe SNR is important. Schloerb et al., (1999) use a model of the turbulence effects to extract the visibility modulus.

Due to the atmospheric turbulence affecting the wavefronts before recombination, measurements of V are biased by a random factor depending on the seeing quality. Instrumental flaws leading to optical aberrations and non-balanced flux between the two beams modify the measured visibility modulus as well. It is, therefore, important to calibrate each measure on an object by measuring V on an non-variable unresolved source (e.g., a farther star) in the neighborhood of the studied object and at the same turbulence condition, i.e. right away after data acquisition on the studied object. To reproduce the instrumental conditions, the calibrator must roughly be as bright as the object to calibrate.

5. Image reconstruction

Interferometers with two apertures have limited possibilities for image reconstruction due to the absence of phase visibility recovering. Objects assumed with circular symmetry ("standard" stars) may be reconstructed with two-aperture interferometers. However, a problem comes from the limb-darkening of the stars observed. The radial intensity profile of a star may be given (Hestroffer, 1997) by:

$$I(r) = I(0)\left(1 - \frac{r^2}{R^2}\right)^{\alpha/2}, \tag{4}$$

where R is the radius of the star and α is the limb-darkening factor depending on the stellar atmosphere.

Many interferometers cannot measure low visibilities existing at high angular frequency (i.e, when $\sqrt{u^2 + v^2}$ is large), beyond the first zero of the visibility function. Reconstructions are, therefore, ambiguous and neither the diameter nor the limb-darkening factor may be accurately determined. Usually, α is an *a priori* information given by the stellar atmosphere model. The diameter is, therefore, deduced from α and the interferometric data.

Binary systems have already been characterized by optical stellar interferometry. The expression of two unresolved sources, i.e. a binary system, is $O(\mathbf{x}) = a\delta(\mathbf{x} + \mathbf{x}_0) + b\delta(\mathbf{x} +$

$\mathbf{x}_0 + \mathbf{x}_s)$, where $|\mathbf{x}_s|$ is the angular separation. The visibility modulus corresponding to this function at $\mathbf{u} = (u, v)$ is, therefore:

$$|\widehat{O}(\mathbf{u})| = \sqrt{(a-b)^2 + 4ab\cos^2(2\pi \mathbf{u}.\mathbf{x}_s)}. \tag{5}$$

It is then useful to use a technique called "super-synthesis": the (u, v) plane is swept during an observation lasting several hours, due to Earth rotation. If we note B'_{EW} and B'_{NS} the orthogonal East-West and North-South components of the baseline vector at the ground of an interferometer located at the terrestrial latitude θ_l, the (u, v) point sampled from a star of declination δ_*, when its hour angle is H, is given by:

$$\begin{cases} u = (\mathrm{B}'_{EW}\cos H - \mathrm{B}'_{NS}\sin\theta_l \sin H)/\lambda \\ v = (\mathrm{B}'_{EW}\sin\delta_* \sin H + \mathrm{B}'_{NS}\,(\sin\theta_l \sin\delta_* \cos H + \cos\theta_l \cos\delta_*))/\lambda \end{cases} \tag{6}$$

After a large variation of H, several visibility moduli are therefore measured at different (u, v) points and allow to determine the parameters (a,b and $\mathbf{x}_s$) of the system by fitting the function described by Eq. 5.

Reconstruction of more complex images involves the knowledge of complex visibilities. The phase of a visibility may be deduced from closure-phase terms (Jennison, 1958) using three telescopes (i.e., wrapped sums of the phases of the three visibilities, including instrumental and atmospheric biases, sampled by the network at a given configuration). Closure-phase in optical interferometry has already been used (Baldwin et al., 1998, Hummel, 1998) for bright objects like the Capella binary system. Process after data acquisition consists of phase calibration and visibility phase reconstruction from closure-phase terms by techniques similar to bispectrum processing. From complex visibilities acquired from an array with a large number of aperture, it is possible to reconstruct the image by actually interpolating the function in the (u, v) plane. This has been done in radio-interferometry for a few decades. The most popular algorithm for reconstructing image from (u, v) plane samples is named CLEAN (Högbom, 1974). CLEAN subtracts iteratively, from the image given by the inverse Fourier Transform of the visibilities measured on the object (the "dirty map"), a fraction of the image given by the array from an unresolved source (the "dirty beam") centered on the maximum value of the dirty map. However, this simple algorithm is subject to instability problems leading sometimes to wrong results. More robust versions of CLEAN have been designed (Cornwell, 1983, Dwarakanath et al., 1990). Among alternative algorithms for image reconstruction in aperture synthesis are maximum entropy method (MEM) and WIPE (Lannes et al., 1997). It can be proved (Maréchal et al., 1997) that both MEM and WIPE derivate from a common principle known as "maximum entropy on the mean".

6. Space-borne interferometers

As classical astronomy at visible and infrared wavelengths already did it (NASA's Hubble Space Telescope, ESA's Infrared Space Observatory), long-baseline optical and infrared interferometry will, in the next years, take advantage of observing from outer space (absence of atmospheric turbulence, observation possible at any wavelength and for long periods, easy cooling of optics and detectors). However, the first projects for a space interferometer (FLUTE, TRIO) were proposed about two decades ago (Labeyrie et al., 1980, 1982a, 1982b). The main difficulty was to develop a technology featuring high-precision positioning as well as toughness required for space operation. Size and weight issues must also be addressed, depending on the chosen orbit. For example, if one wishes to reach the Lagrangian point 2 (where the Sun and Earth gravitations are equal, stabilizing, therefore, any space-borne instrument), then the maximum payload mass of an Ariane V european launcher must be 4998 kg.

6.1. Astrometry from space

The accurate determination of star angular positions will provide crucial data for astrophysics. For example, precise parallax distances of cepheids will help to establish a period/absolute magnitude relationship in order to calibrate distances of galaxies, thus reducing the uncertainty on the value of H_0. For some galaxies, distance from Earth could be computed by tracking the stars of the lower and upper sides of the observed galaxies, yielding its apparent transverse velocity $v_t = v_0/D$, where v_0 is the actual edge velocity and D the distance from Earth. Using spectroscopic ground-based measurement giving the radial velocity $v_r = v_0 . \sin i$ (where i is the disk inclination), one can deduce D:

$$D = \frac{v_r}{v_t \sin i}. \quad (7)$$

The quest for extra-solar planets (exo-planets) is another challenge for high-precision astrometry. A planet orbiting around a star causes a revolution of the star around the center of gravity defined by the two masses. Like galaxy velocity, this periodical short motion known as "wobble" has a radial counterpart measurable from ground by spectrometry. Thus, if Doppler-Fizeau effect measurements have already led to detect from Earth jovian planets around stars, like for example 51-Peg (Mayor and Queloz, 1995) or 47-Uma (Marcy and Butler, 1996), smaller planets might be detected by measuring the stellar photocenter motion due to the wobble.

Very valuable astrometry results from space have already been obtained by the Hipparcos satellite (Perryman, 1989). Hipparcos used phase shift measurement of the temporal evolution of the photometric level of two stars seen drifting through a grid. The successor of Hipparcos, Gaia (Lindengren and Perryman, 1996), will probably use the same technique with improvements, yielding more accurate results on a larger number of objects. However, only space-borne interferometers will achieve very high precision angular measurements.

For an interferometer consisting of two apertures separated by a baseline **B**, the external optical delay d, while an object with altitude θ is observed in a broad spectral range (i.e. white light), is:

$$d = |\mathbf{B}| \times \cos\theta. \tag{8}$$

This delay can be deduced from the position of the optical delay-line of the instrument set up such that the central fringe of the interference pattern appears in a narrow observation window. The position, as well as $|\mathbf{B}|$, are measured by laser metrology. Hence, θ is deduced with a high precision. For a space-borne interferometer, the issue is to find a reference for the angle measured. Usually, a grid of far objects like quasars are used as a reference frame. Then, two modes of observation are possible: the "wide-angle" and the "narrow-angle" modes. In wide-angle mode, the large angle difference between the reference and the studied object usually requires collector motions. In narrow-angle, the two objects are in the field of view of the instrument, therefore, no motions are required and the accuracy of the measurement is improved. However, it is difficult to have always a correct reference star within the field of view for any studied object. Narrow-angle astrometry is, therefore, more suitable for wobble characterization. Figure 8 depicts the principle of an interferometer for astrometry.

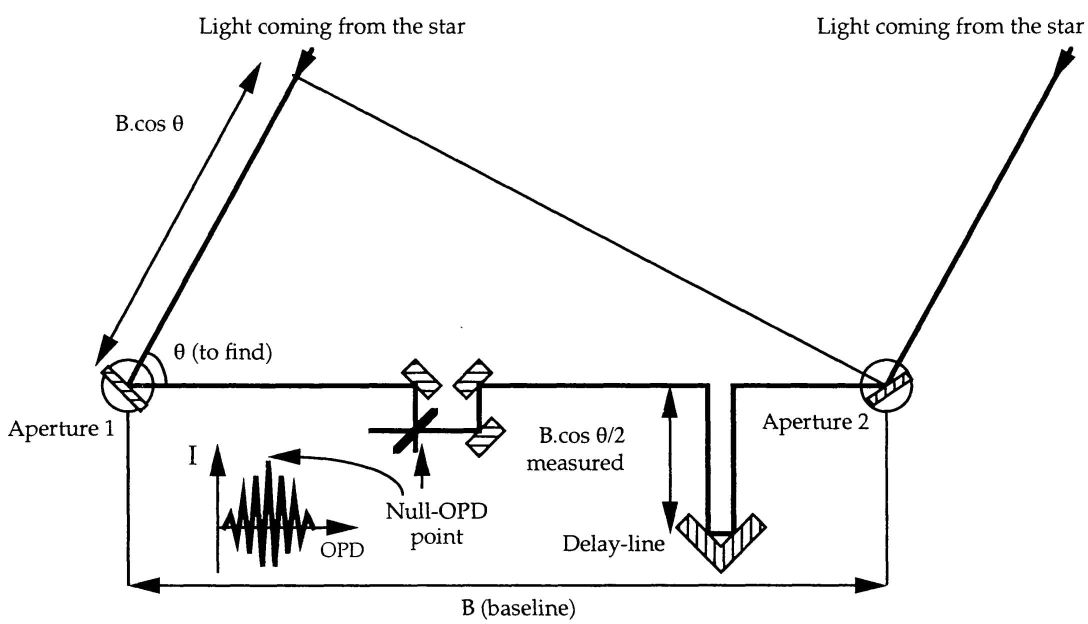

Figure 8. Principle of an interferometer for astrometry.

6.2. First space-borne interferometers

The expected pioneer of this new generation of scientific spacecrafts is "Space Technology 3", or ST3 (Gorham et al., 1999), formerly known as "Deep Space 3". This NASA's mission, scheduled for 2003, consists of two independent free-flying elements launched into an Earth-trailing heliocentric orbit. One is a collector sending light from the observed object to the second element featuring another collector, an optical delay-line and a beam recombiner. The aim of ST3 is the demonstration and validation of technologies that might be used for future space-borne interferometers like SIM or TPF (see further). Thus, the two elements of ST3 should be able to move up to 1 km from each other, thanks to ionic micro-engines, while being controlled by a laser metrology. However, the designed delay-line of ST3 can delay up to 20 m of optical pathlength only. A 200 m maximum projected baseline would, therefore, be possible with 1 km spacecraft separation. More than just a technology experiment, ST3 will be used as an imaging interferometer for studying Wolf-Rayet or Be stars (Linfield, 1999).

After ST3, SIM (Space Interferometry Mission) will be the next space-borne interferometer built and launched by NASA (Unwin et al., 1998). The main goal of SIM will be to collect the new high-precision astrometry results (see above), including the possibility of jovian planet detection around stars up to 1 kilo-parsec distant and terrestrial planet detection around nearby stars. The final design of SIM, known as "SIM Classic" has recently been decided (Unwin, 1999). It consists of one free-flyer with a 10 m boom supporting 30 cm collectors. The expected angular accuracy is 1 μas in narrow-angle mode (with a 1° field of view) and 4 μas in wide-angle mode. The sensitivity for astrometry is $m_V = 20$ after four hour integration. SIM will work in the visible spectrum (0.4 to 0.9 μm). In order to get an accurate knowledge of the baseline vector **B** for wide-angle astrometry without collector motions, SIM will feature two auxiliary interferometers, aimed at reference stars ("grid-locking"). The schematic design of the SIM is depicted in figure 9.

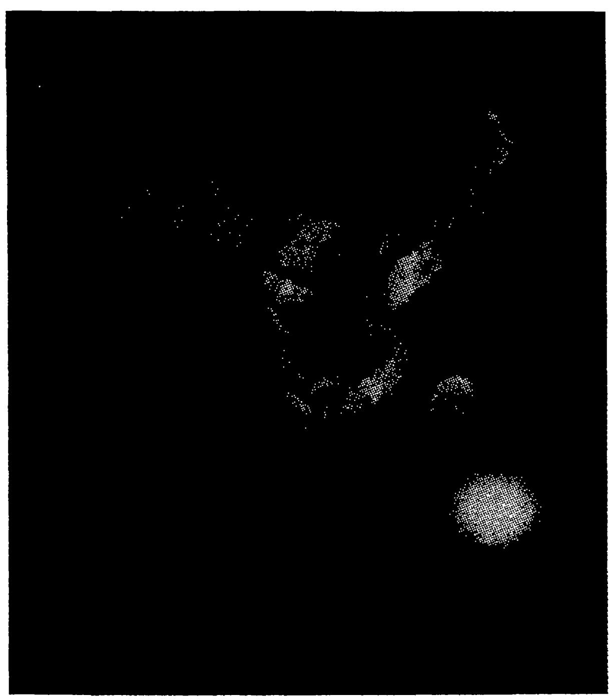

Figure 9. The schematic design of the SIM (Courtesy: NASA/JPL/Caltech).

Besides its abilities for astrometry, SIM will feature a nulling mode. Like coronography, the nulling is a technique used for masking a bright central object in order to reveal its fainter environment (Bracewell and Macphie, 1979). Basically, a nulling system is an interferometer with a π phase shift introduced in one beam. Therefore, the central fringe of the interference pattern is dark, allowing the fringe pattern from a faint object to appear. The quality of a nulling is defined by the "null depth" N:

$$N = (1 - V\cos\varphi_e)/2 \approx (\pi\sigma_{\rm OPD}/\lambda)^2, \tag{9}$$

where V is the fringe visibility modulus, φ_e the phase error between the two recombined beams and $\sigma_{\rm OPD}$ the standard deviation of the optical path difference between the two beams. Nulling at $N = 25,000$ has been obtained with laser light in laboratory (Serabyn, 1999). The nulling system of SIM is expected to reach $N = 10,000$ with white light.

SIM should be launched in 2005 into an Earth-trailing heliocentric orbit and be operational from 2006 for a five-year mission.

6.3. Searching for life on other planets

The old, somehow philosophical, question "Is Earth the only planet sheltering life or not?", might be answered in the next decades, thanks to interferometry. The knowledge of the chemical composition of any planetary atmosphere gives hints about the likeliness to find carbon-based life, as we know it, on this planet. Lovelock (1965) has suggested that the simultaneous presence on Earth of a highly oxidized gas, like O_2, and a highly reduced gas, like CH_4 and N_2O is the result of the biochemical activity. However, finding spectral signatures of these gases on an exo-planet would be very difficult. An alternative life indicator would be ozone (O_3), detectable as an absorption line at 9.6 μm. On Earth, ozone is photochemically produced from O_2 and, as a component of the stratosphere, is not masked by other gases. Finding ozone would, therefore, indicate a significant quantity of O_2 that should have likely been produced by photosynthesis (Léger et al., 1993). Moreover, for a star like the Sun, detecting ozone can be done 1000 times faster than detecting O_2 at 0.76 μm: estimates made by Angel and Woolf (1997) show that the requirements for planet detection in the visible with an 8 m telescope are not matchable with current technology.

One of the imagined instruments for ozone search on exo-planets is "Darwin" (Penny et al., 1998), a.k.a. IRSI (InfraRed Space Interferometer), a project selected by ESA as a "cornerstone mission". The aim is the discovery and characterization of terrestrial planet systems around nearby stars (closer than 15 pc) by direct detection (i.e. involving the detection of photons from the planet and not from the star as it is done with Doppler-Fizeau effect detection or wobble detection). The design of this instrument has not been established yet, but some features will likely to be found in the final version of Darwin.

Basically, Darwin will have to overcome two major difficulties for achieving Earth-like planet detection. The first one concerns stellar light quenching. Interferometric nulling techniques will obviously be employed to address this issue. Severe requirements about the optical quality of the nulling device might involve spatial filtering (Ollivier and Mariotti, 1997), by pinhole or single-mode fibers, to smooth the beam wavefronts. The second difficulty is the expected presence of exo-zodiacal light (infrared emission from the dust surrounding the observed star).

Several solutions for the instrument design have, therefore, been imagined. The first one consists of five free-flying collectors (1 to 2 m telescopes) rotating around a central recombiner. The image of the exo-planetary system is constructed after a 2π rotation of the system. The odd number of apertures enables a recovery of the signal from a planet (which is an asymmetrical object from the axis of rotation defined by the star) drowned in the signal from the exo-zodiacal disk (which is a symmetrical object around the star). An alternative configuration, recently imagined, consists of six collectors arranged to form a triangle (Mariotti and Menesson, 1998). In this configuration, no rotation of the system is required. Darwin is expected to be launched in 2009 into an orbit at 5 AU from the sun, in order to reduce the illumination by solar zodiacal light.

A project named TPF (Terrestrial Planet Finder), very similar to Darwin/IRSI is currently persued by NASA (Beichman, 1998). Like Darwin, the final design has not been decided yet. The current version (Lawson et al., 1999) features four aligned 3.5 m free-flying telescopes and a central recombiner. The baseline from the two most separated telescopes can span from 75 m to 1 km. Like the original design of Darwin, the collectors of TPF will rotate around the recombiner for planet detection. In this case the maximum baseline is 135 m. For planet imaging, telescopes will move along parallel straight lines and could be separated by 1 km. Instrumentation for spectroscopy on TPF will include a $R = 30$ spectrometer working between 7 μm and 20 μm for planet detection, and a $R = 300$ spectrometer working between 3 μm and 30 μm for imaging. The expected time to find a planet and then to determine whether ozone is present in its atmosphere should be 15 days for each star zeroed in on. The launch of TPF is expected in 2010. Its five-year mission will start one year later. Instead of a far orbit location as Darwin is supposed to reach, TPF will be placed on a Earth-trailing orbit or at the Lagrangian point 2. Despite the problem of solar zodiacal light (that is expected to be overcome by using telescopes larger than Darwin's), such orbits provide easier radio-transmissions, a larger available solar power and a heavier payload possible for the launcher. Figure 10 depicts the conceptual design of TPF

6.4. Long-term perspective

Space-borne interferometry projects for years spanning from 2020 to 2050 already exist. However, the reader should be aware that such projects must be regarded as drafts for future instruments. No one can forecast, today, how future space-borne interferometers will actually look like.

For the post-TPF era, NASA has imagined an enhanced version featuring four 25 m telescopes and a $R \geq 1000$ spectrometer. This interferometer would be able to detect

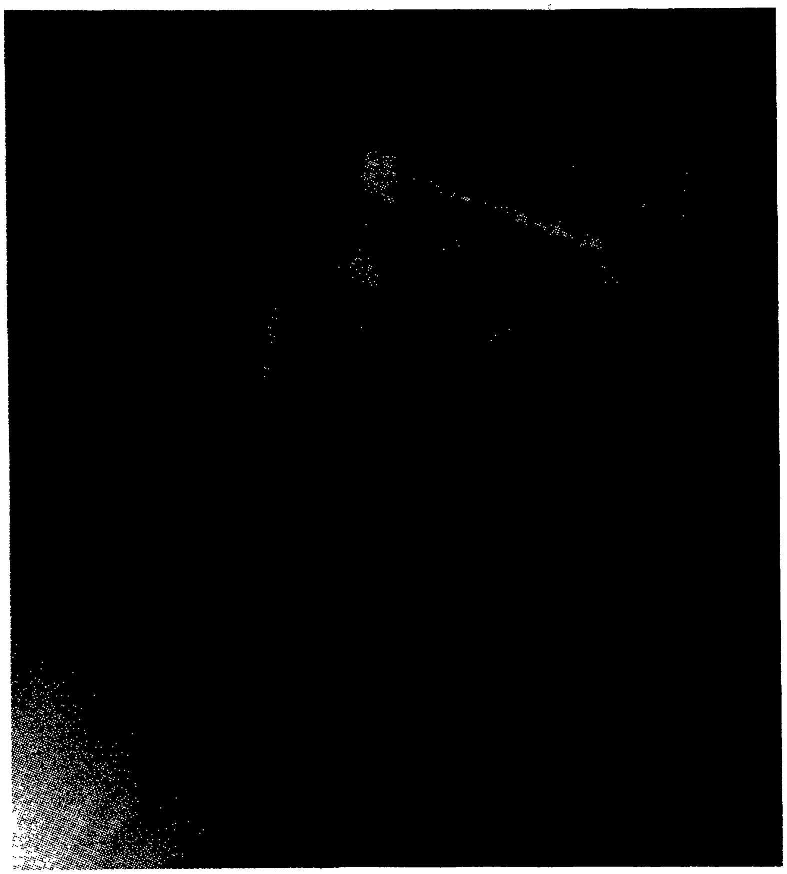

Figure 10. The conceptual design of the TPF (Courtesy: NASA/JPL/Caltech).

on an exo-planet lines of gases directly produced by biochemical activity. The next step proposed by NASA is an array of 25 telescopes, 40 m diameter each, that would yield 25 × 25 pixel images of an Earth-like planet at 10 pc, revealing its geography and eventually oceans or chlorophyll zones.

A comparable project has been proposed by Labeyrie (1999). It consists of 150 telescopes, 3 m diameter each, forming an interferometer with a 150 km maximum baseline. Such an instrument would give a 40 × 40 pixel image of an Earth-like planet at 3 pc, providing the same information as described previously.

8. Conclusions

The angular resolution of any stellar object in the visible wavelength can vastly be improved by using long baseline interferometry. The angular diameter for more than 50 stars have been measured (DiBenedetto and Rabbia, 1987, Mozurkewich et al., 1991, Dyck et al., 1993) with an accuracy of better than 1% in some cases using the ground-based long baseline amplitude interferometers at optical and IR wavelengths. Apart from the measurements of the diameters, distances, masses on the stellar surfaces, among others, this technique can detect the morphological details, viz., (i) spots and flares, (ii) granulations, (ii) oblateness etc., of giant stars. Eclipsing binaries (Algol type) which show evidence of detached gas rings around the primary are also good candidates for long baseline interferometry. The potential of this type of interferometer can be envisaged in determining the fundamental astrophysical informations of circumstellar envelopes such as, the diameter of inner envelope, colour, symmetry, radial profile etc. The objectives of very large array in optical/IR wave bands range from detecting other planetary systems to imaging the black hole driven central engines of quasars and active galaxies.

Several long baseline interferometers are either in operation or under development at various stages. Rapid increase in the scientific output at optical, as well as at infrared wave bands using these interferometers can be foreseen at the begining of this millennium. With improved technology, the long baseline interferometric arrays of large telescopes fitted with high level adaptive optics system that applies dark speckle coronograph (Boccaletti et al., 1998) may provide snap-shot images at their recombined focus using the concept of densified-pupil imaging (Pedretti and Labeyrie, 1999), and yield improved images and spectra of objects. One of the key areas where the new technology would make significant contributions is the astrometric detection and characterization of exo-planets.

However, the role of smaller interferometers should not be neglected, since such instruments could be useful for long observations of binary systems, testing new focal instrumentation designed for larger interferometers, or observing at short wavelengths (blue, UV). Moreover, this class of interferometers would be easily accessible to a broader community of astronomers and might be employed as educational tools.

On the other hand, space-borne LBIs would provide the best ever spatial resolution of faint objects as the fringes can be recorded with longer integration time. The greatest advantage of such a project is being the absence of atmospheric turbulence. The bright prospects of LBI programmes can be witnessed from the future space interferometers like SIM, ST3 and Darwin which are effectively funded projects that will become an essential tool at the cutting edge of astronomical research in the new millennium.

Acknowledgments: The authors thank Dr P. R. Lawson at Jet Propulsion Laboratory, USA and Dr O. Lardière at Observatoire de Haute Provence, France, for photographs used in this paper. The service rendered by Mr. B. A. Varghese, Indian Institute of Astrophysics, Bangalore, India is also gratefully acknowledged. One of the authors Dr S. Morel is grateful to DGA-DRET (the scientific research office of the French Ministry of Defense) for having funded his post-doctoral stay at IOTA, and to JPL for its useful documentation and lectures.

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