OPTICAL INTERFEROMETRY – A PRACTICE PRIMER

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Abstract. The existing and planned interferometers differ largely in the size of telescope area, baseline length and wavelength at which they operate. In this article we focus on the common principle between all of them and discuss the three main ingredients of an interferometer: the light collectors, the delay lines and the beam combiner. We take a look into the different approaches taken, e.g. beam travel in vacuum or air, the use of spatial filters, interferometer layouts etc. Furthermore, we describe the subsystems which are helping in the formation of fringes, namely adaptive optics, fringe trackers and phase reference systems.

Keywords: optical interferometry

1. Introduction

There are ten optical interferometers in operations today: CHARA (ten Brummelaar, 2002), COAST (Haniff et al., 2002), GI2T (Mourard et al., 2002), IOTA (Traub, 2002), Keck (Boden, 2002), MIRA (Nishikawa, 2002), NPOI (Mozurkewich), PTI (Lane, Colavita and Boden, 2002), SUSI (Tango, 2002) and VLTI (Glindemann et al., 2002). Several more went out of service. Although they are very different in their appearance (e.g. they have telescope sizes between a few cm and more than 10 m), the wavelength regime they operate in (somewhere between 400 nm and 13 μm), the modes of operation (pure visibility measurements, closure phases, phase referencing, wide and narrow angle astrometry, nulling), they all utilize the same underlying physical principles and use more or less the same kind of hardware. In this article we want to describe the basic technology that is needed to make an optical interferometer work.

When we talk about optical interferometers in this paper, we think of interferometers which work at visible, near- or mid-infrared wavelengths and make a direct detection of fringes. We would like to separate these types of interferometers from e.g. heterodyne interferometers like the ISI (Danchi et al., 2002), which mix the signal of each telescope with a local oscillator and form the fringes electronically, or the intensity interferometer (Hanbury Brown, Davis and Allen, 1967), which was determining correlations of photon arrival statistics instead of making fringes.

For a good overview about the status of optical interferometry in general, the reader is referred to (Quirrenbach, 2001) and for the historic context to (Shao and Colavita, 1992).

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In this article we will discuss first the key ingredients that are needed to make an interferometer work. This is followed in section 3 by the devices which make the life of an interferometrist easier and the limiting magnitude of the interferometer fainter. In the next section we describe the insight that has to be put into the effort of designing the interferometer, before we discuss in section 5 briefly dual feed systems and nulling. We conclude in section 6 with what challenges optical interferometry will face in the future.

2. Key Ingredients

An interferometer can essentially consist out of the following components: two telescopes and a beam combiner. Furthermore, optical trains are needed to tie the components together, i.e. transport the light from the two telescopes towards the beam combiner. If the telescopes are on the same mount – as for the Large Binocular Telescope (Herbst, 2002) – or the telescopes move to keep the optical path difference to 0 – like the intensity interferometer did (Hanbury Brown, Davis and Allen, 1967) or as proposed for the 20/20 (Angel, 2002) – then this is all it needs. Most interferometers have telescopes which are fixed to the ground, and thus need delay lines to compensate for the optical path difference (OPD) between the arms of the interferometer, while the source moves across the sky. Instead of using a delay line, in the I2T (Labeyrie, 1975) and the first version of the GI2T the beam combination table was moved.

2.1. Telescopes

The main task of the interferometric telescopes as in any single dish operation is to collect photons. A rigid design is needed to avoid any introduction of optical path difference due to vibrations, as for all components of the interferometer. As a golden rule, all telescopes of an interferometer should be of the same type, with the same orientation of mirrors and the same coatings on all conjugating optical surfaces to control differential polarization.

Smaller interferometers employ usually siderostats, since they are cost effective and very sturdy. Their drawbacks of complicated field rotation and changing elliptic aperture shapes are of minor concerns for interferometers. Interferometers with larger apertures usually use alt-az mounted regular telescopes equipped with a Coudé train to inject the light beams into the interferometer. Examples of interferometric telescopes can be found in Figure 1.

2.2. Delay lines

The delay lines have to compensate the optical path difference (OPD) for all baselines in an interferometer. To do this, they have to cancel the OPD at any given time, i.e. follow the sidereal delay while the object moves across the sky.

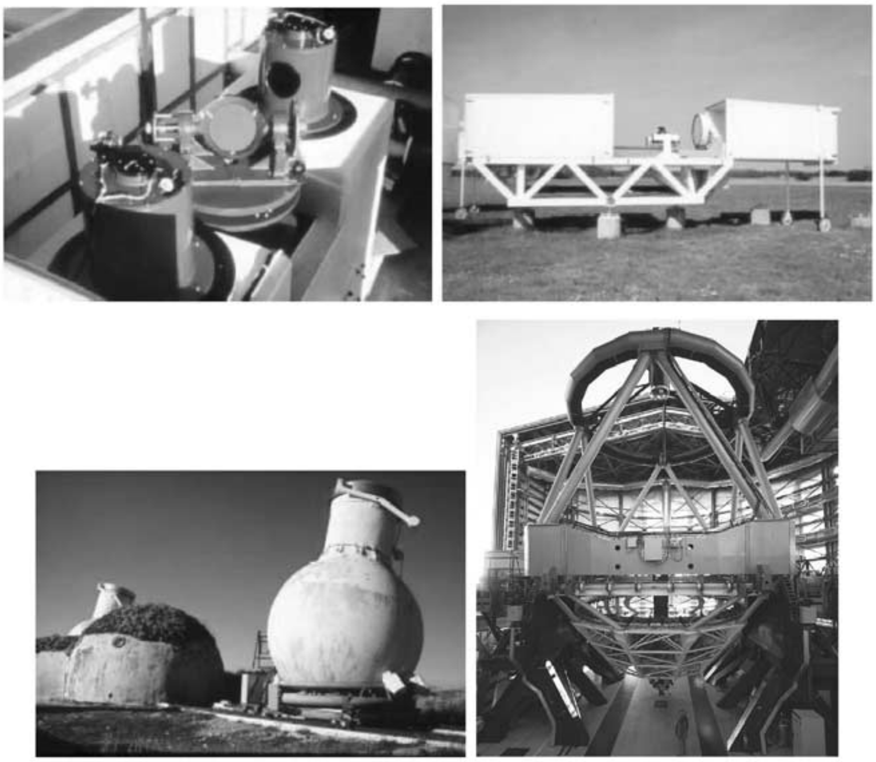

Figure 1. Interferometric telescopes: on the top one can see the siderostats used by SUSI (left) and COAST (right), on the bottom left the special interferometric design of the GI2T telescopes and on the bottom right one of the VLTI's 8 m Unit Telescopes.

An interferometer with N telescopes or better with N arms needs delay lines for the first N-1 arms. The last arm needs an optical device which has the same mirrors under the same angles as the delay lines. Many interferometers put another delay line onto this arm for convenience and more flexibility.

Apart from the actual number of delay lines used, there are also different ways in which the total OPD can be canceled. The VLTI implements only one moving delay line per arm with a sufficiently long compensation range. The Keck uses so-called fast delay lines which compensate the sidereal motion, while at the same time compensating most of the OPD with long delay lines in which mirrors can be moved and clamped to give various compensation ranges. The GI2T has one delay line with a short range of compensation length and moves its telescopes into a position so that this range is enough to compensate the overall OPD.

The optics of delay lines are typically either a roof mirror or a cat's eye. The cat's eye has the advantage that light which enters the delay line under an angle α leaves it under the same angle, while it leaves a roof mirror under the angle $-\alpha$.

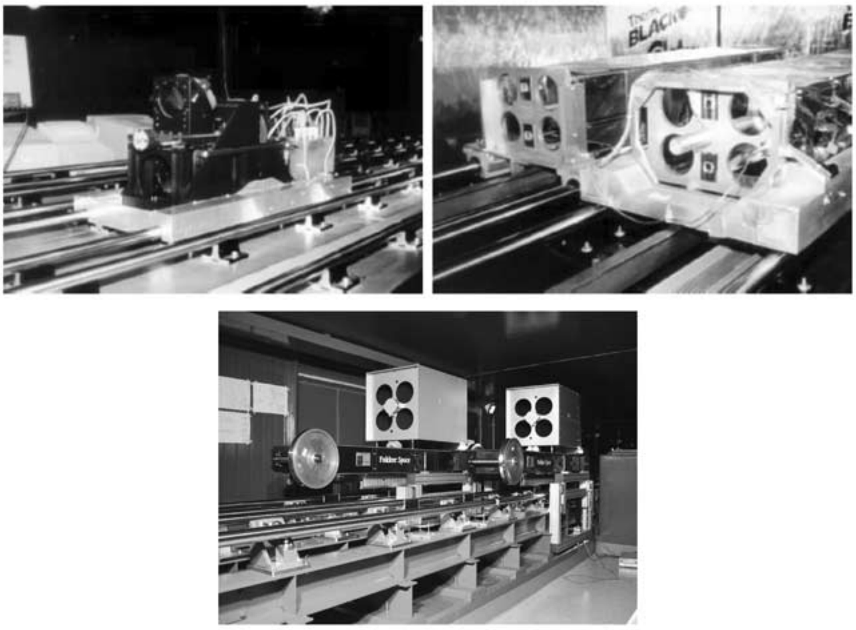

Figure 2. The delay lines of three different interferometers: COAST (top left), PTI (top right) and VLTI (bottom).

Thus, if a cat's eye is moving slightly misaligned, the beam is still reflected back into the direction where it came from.

Delay lines can be moved in various ways, with linear motors, voice coils or piezos. Typically they consist of a composition of these components, e.g. a linear motor for the coarse and a piezo for the fine positioning. This mix of devices makes it possible to achieve the positioning requirements of the delay lines with an accuracy of tenths of nanometers over a stroke length of tenths of meters.

Figure 2 shows various implementations of delay lines.

2.3. Beam combination

A beam combiner brings the beams from the telescopes close enough together so they can interfere. If the beam combination scheme requires the coding of the fringes in time, a device to modulate the OPD between the beams is required. Further, some type of detector to record data is needed.

There are two different ways to combine beams in a beam combiner: in a multiaxial beam combiner the beams are placed adjacent to each other and form a fringe pattern in space. In a coaxial beam combiner, the beams are added on each other, for example with a beam splitter. The fringes are produced in time by modulating the OPD between the two beams. Figure 3 illustrates the two combin-

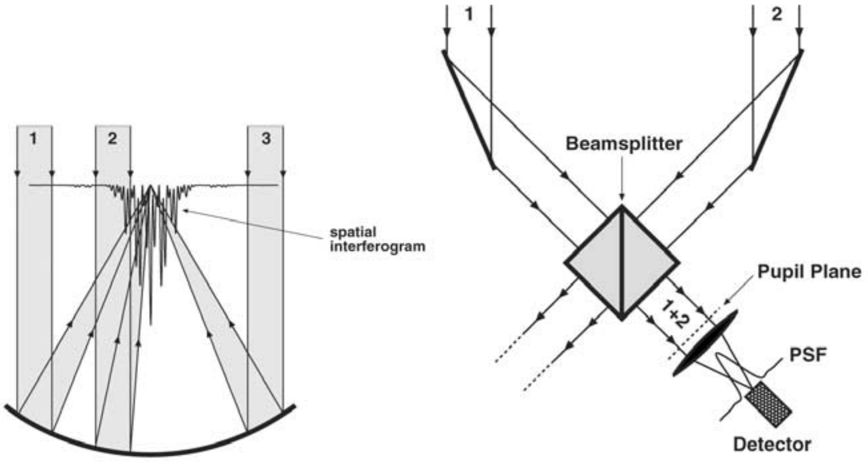

Figure 3. Fringe combination schemes: multiaxial (left) and coaxial (right). An OPD modulating device has to be used in one of the arms of the coaxial beam combiner to form fringes.

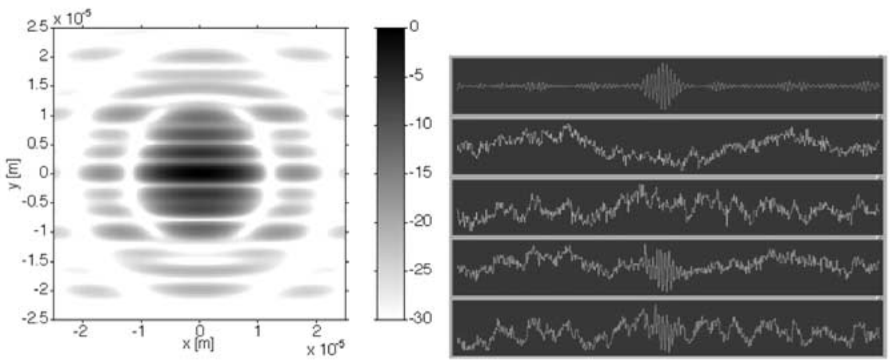

Figure 4. The fringes resulting from multiaxial and coaxial beam combination: on the left one can see a simulation of fringes similar to the ones which will be produced by the AMBER instrument on VLTI. The right panel shows fringes as observed by the VINCI instrument on VLTI. The lower two scans show raw fringes in the two interferometric channels, the two scans above give the photometric signals, and the upper row shows the compensated and filtered fringe.

ation schemes and in Figure 4 one can see how the data resulting from the beam combination looks like.

The actual implementation of a beam combiner is done usually in bulk optics, which take space and are susceptible to misalignments. Another type of beam combiners is made out of single mode fibers, which are not only combining the light within the fibers, but also serve as spatial filters (Coude du Foresto, Maze and Ridgway, 1993). Lately, progress in the production of integrated optics has allowed

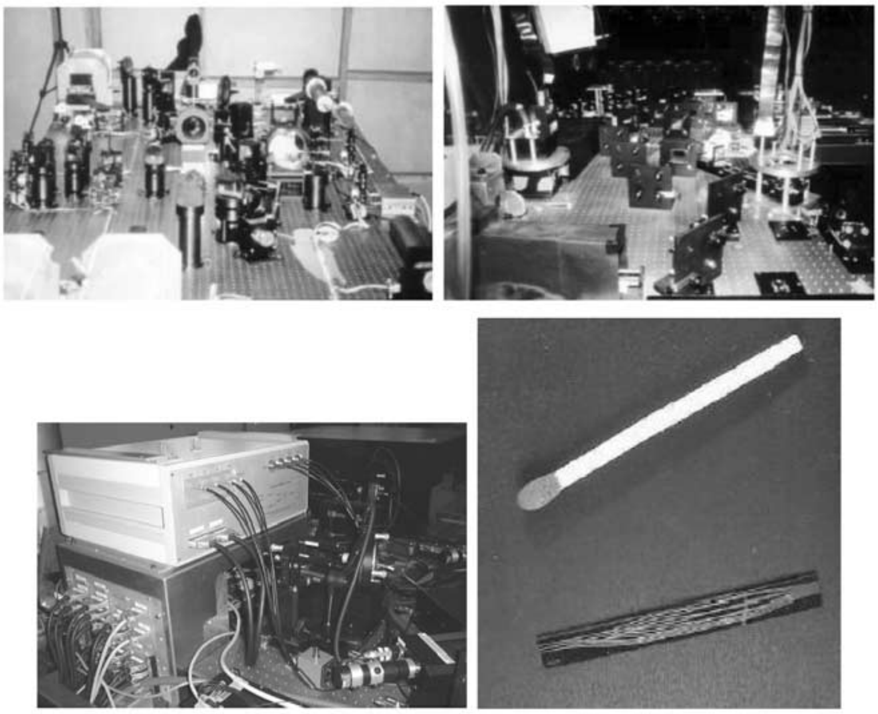

Figure 5. Different types of beam combiners: in the upper row one can see the bulk optics assemblies of SUSI (left) and COAST (right). In the lower row the fiber optics beam combiner box of VINCI on VLTI (named MONA, left) and the integrated optics beam combiner IONIC (right) are shown.

to build beam combiners of the size of a coin (Malbet et al., 1999), (Berger et al., 2001). Different types of beam combiners can be found in Figure 5.

When using more than two telescopes, one has to make a choice how to combine the signals on the different baselines. The easiest way is to split the light of the N beams into N-1 parts and interfere all beams pairwise. Another approach is to put all beams onto one detector and encode the different baselines on different spatial or temporal frequencies. By doing this one has to take special care to avoid cross talk between the different baselines, which could bias the signals significantly. A mix of the two schemes is used at the NPOI, where six telescopes are combined in three beam combiners, which each combine four telescopes. The complexity rises for the pairwise scheme with the number of baselines, for the all-on-one scheme only with the number of telescopes. The pairwise combination also has drawbacks when it comes to closure phases, since these are affected by drifts between the beam combiners.

The signal-to-noise ratio (SNR) between pairwise and all-on-one combination is similar, since in one case the light has to be distributed between the beam combiners, in the other case it has to be split between the different encoder frequencies.

It is not clear if it is better to combine e.g. eight telescopes all at once at a lower SNR, or to combine four telescopes twice and getting all baselines and closure phases sequentially. Beside the SNR one also has to take calibration issues into account. The debate about how to combine many telescopes is far from over.

3. Adaptive Optics, Spatial Filtering, Fringe Tracker, and Variable Curvature Mirror

Since the light of two (or more) telescopes has to be combined, it is necessary to bring the light of them onto the same spot in an image plane. Tip-tilt sensors for each telescope are employed to ensure the image stability needed. If the telescopes are larger than the diameter of the atmospheric turbulence cells (the Fried Parameter r_0), then the telescopes have to be equipped with adaptive optics to ensure the maximum flux being available for the beam combination. Finally, a fringe tracker stabilizes the fringes, which are otherwise moved backwards and forwards in OPD by the atmospheric piston.

3.1. TIP-TILT AND ADAPTIVE OPTICS

While in imaging systems tip-tilt and adaptive optics (AO) are used to make sharper images, in optical interferometry they are used similar as in spectrographs. Instead of putting as much light as possible onto a slit, here the goal is to put as much light as possible onto a spatial filter.

The main tradeoff for these systems is between costs (we are talking about as many AO systems as telescopes) and performance.

One also has to consider the optimum position for the wavefront sensor. While a sensor at the telescope is not able to correct errors which result from the optical path between the telescopes and the beam combiner, a sensor in the laboratory leads to sensitivity loss and very likely to alignment problems. A possible solution is a higher order AO system at the telescope and a slower tip-tilt corrector in the laboratory.

3.2. SPATIAL FILTERING

Wavefront errors lead to a degradation of the measured visibility. The interfering wavefronts have to have exactly the same shape to give the maximum degree of coherence. A spatial filter ideally removes inhomogeneities of the individual wavefronts (and thus makes them similar), at the cost of reducing the amount of light which is available for beam combination. One can also say that a spatial filter acts as a low pass filter for the wavefront.

There are two different implementations of a spatial filter: single mode fibers and pinholes. While single mode fibers are removing the wavefront errors nearly perfectly, pinholes can be effective in the regime of a small ratio of telescope diameter over r_0, and are usually used at wavelengths where no single mode fibers exist.

3.3. Fringe tracking

A fringe tracker stabilizes the fringes within a fraction of a wavelength so that the scientific instruments can integrate much longer than the coherence time of the atmosphere would allow.

Although this looks very good at a first glimpse, it is not so obvious that it actually helps a lot. If the fringe tracker is able to track the fringes on the source, this means that there is enough signal in a coherence time interval to measure the phase of the fringes with high accuracy. The science instrument should then also be able to detect and measure the fringe without any problems. But there are possible scenarios where a fringe tracker helps a lot:

- Fringe tracking is done in a wide band while the science instrument uses high spectral resolution.
- The source can be tracked at the fringe tracker wavelength while not at the scientifically interesting wavelength (wavelength bootstrapping).
- Fringes are tracked on two shorter baselines while the science instrument is integrating on a long baseline (baseline bootstrapping).
- Fringes are tracked on an off-axis source in dual feed mode.

3.4. Variable curvature mirror (VCM)

The distance from the telescope entrance pupil to the beam combination instrument is variable in an interferometer due to the moving delay line. Without an active element in the optical train no pupil imaging is possible. Pupil imaging is necessary if one wants to put the telescope pupil on a cold stop, e.g. when observing in the thermal infrared, or in the case of homothetic mapping where the entrance pupil of the interferometer has to be mapped onto the exit pupil of the interferometer in all three coordinates to achieve a larger field of view. The variable curvature mirror sits e.g. in an image plane within the delay line and changes its radius of curvature so the entrance pupil is relayed to a given position (Ferrari et al., 2002).

4. Optical Path, Array Layout, Alignment and Interferometer Control

4.1. Beam transport

An issue which is always taking much attention is how the beams are actually transported from the telescopes to the beam combiner. The light can be transported in air, in vacuum or in fibers.

A travel in air introduces additional wavefront errors due to internal turbulence. To keep these errors to a minimum, a stable environment is required. The two main concepts are the wine cellar approach, where the environment is built underground and left undisturbed, and the building-in-building, where the inner building is also kept undisturbed, while the outer building is kept under thermal control. Another problem which is apparent when transporting the beams through air is the differential refractive index for different wavelengths. Figure 6 shows air exposed tunnels and vacuum pipes.

The use of vacuum solves the problem of internal wavefront errors and is mandatory if the beams are traveling over ground in pipes which are heated during day time, resulting in huge turbulence. They can also reduce somewhat the problem of differential refraction. The disadvantage of a vacuum system is, besides the cost of the investment itself, that entrance windows have to be used and the optics are not easily accessible anymore.

Another way to transport the beams, which was proposed by (Froehly, 1982) is to inject the light at the telescope into a fiber and then transport it towards the beam combination laboratory. Although issues like light injection and dispersion within the fiber have to be taken into account when implementing a fiber transport, other infrastructure related problems like light ducts, underground tunnels, or a large number of mirrors, which have to be set under the exact same angles, disappear. A beam transport within fibers is especially attractive for the implementation of an interferometer on an existing telescope array. The OHANA array (Perrin et al., 2002) will transport beams within fibers.

4.2. Array Layout

The layout of an interferometric array has to be optimized to give as good a uv-coverage as possible. The shape of the landscape at the observatory has also to be taken into account. Figure 7 shows some examples of possible interferometer layouts.

4.3. Aligning

Since an optical interferometer has a huge number of optical surfaces, which might be coupled together in various ways, some thoughts have to be put into the alignment strategy. There is a tendency to have a system with light sources and degrees of freedom everywhere to be able to align the optical system. The alternative is an undisturbed and well engineered system which does not require any frequent alignment. A well designed interferometer has an image alignment and a pupil alignment device and everything else is static or adaptive.

4.4. Controlling an Interferometer

Since interferometers can be highly complex systems, one has to invest some effort into the software and hardware which tie the pieces together.

Figure 6. Beam transport in interferometers can run through open air or within evacuated pipes. The left column shows the air tunnels of PTI, SUSI and VLTI (the first two building-in-building, the latter a wine cellar). The right column shows the pipes of PTI and the pipes of CHARA outside and inside the interferometric building (both from top to bottom).

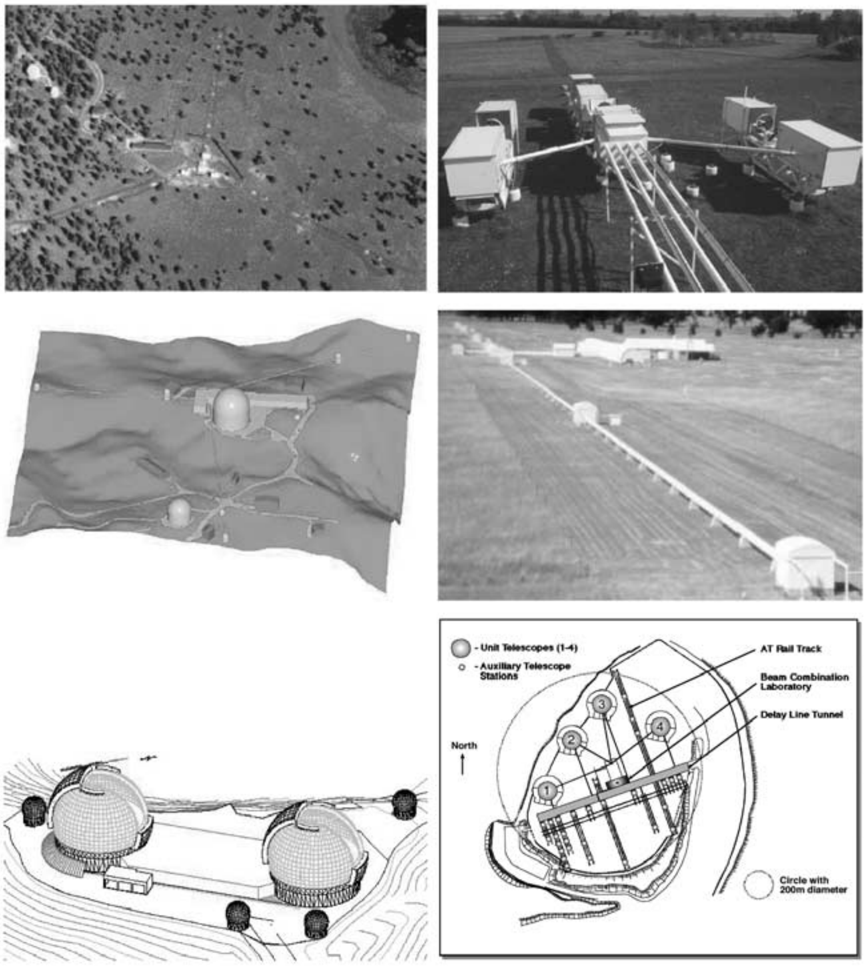

Figure 7. Different strategies for layouts of optical interferometers: the arrays of NPOI, COAST and CHARA (top left, top right and middle left) resemble the shapes of a Y, while SUSI (middle right) is linear, KECK (bottom left) has two perpendicular baselines with their outriggers and the VLTI (bottom right) a field of stations which can populate various shapes.

As an example, we present here the sequence which is foreseen for the 10 μm instrument MIDI on the VLTI 8 m Unit Telescopes, chopping while a fringe tracker is in use. The following cycle has to be repeated with about 2 Hz:

At the start, MIDI and the fringe tracker are on source and MIDI is integrating while the fringe tracker is tracking. Next, both the fringe tracker and the adaptive optics system open their respective loops to not get confused when they do not get any flux from the observed object. The telescope now chops off source and MIDI integrates a sky fringe to determine the rapidly changing sky background. Once this is done, the telescope chops back on source. The adaptive optics can now again close the loop and once this is achieved, the fringe tracker can follow. After all this is accomplished, MIDI will again integrate on source.

ESO's VLTI will be the first general user interferometer. It will be operated in the framework of the VLT data flow system (Ballester et al., 2001).

5. Dual Feed and Nulling

5.1. Dual feed systems

The field of view of an interferometer is usually very small, much smaller than the field of view of the individual telescopes. A dual feed system allows two objects within the telescope field of view to be picked up and being sent independently through the interferometer where they are both combined individually.

The dual feed system makes three kinds of observations possible: observations of faint objects while fringe tracking on a source within the isoplanatic patch, imaging due to direct access to object phase information via phase referencing and narrow angle astrometry.

A dual feed system requires the following components:

The star separator allows the separation of two objects within the field of view at the telescope focus and sends two beams into the interferometer.

A differential delay line compensates the OPD between the two objects.

The metrology measures the internal optical path of the interferometer.

A fringe tracker stabilizes the fringes on one object.

Note that the optics of the interferometer have to be designed in such a way that they can cope with two beams per telescope.

5.2. Nulling

Nulling is not an interferometric technique but an imaging technique which can also be used on interferometers. Nulling introduces a wide band achromatic phase shift of π in one arm which results in destructive interference. In an interferometer the result is e.g. a wide fringe maximum of a planet in the sharp minimum of its parent star instead of a sharp planet maximum in a shallow star minimum.

6. Future Challenges

Optical long baseline interferometry has made huge progress in the last thirty years, delivering science on several facilities, with increasing aperture diameters and baseline lengths. Yet, there are several technologies which still have to be mastered.

Beam transport in fibers has not been successfully implemented in an optical interferometer up to now. If these fibers could coherently amplify the number of photons, subsequent losses could be overcome.

Water vapor very likely has the largest influence on accurate measurements at 10 μm (Meisner and le Poole, 2002). The studies on humidity dependence of the refractive index of air and the consequences on the longitudinal dispersion are just starting.

Alternative concepts for delay lines have to be developed when larger OPDs have to be compensated on baselines much longer than the ones used today.

With a larger number of telescopes and instruments on the same interferometer, intelligent ways have to be found to switch beams. Active integrated optics may be of help here.

The NPOI uses the most complex beam combiner to combine six telescopes. The combination of a larger number of telescopes in bulk optics will require a lot of space. Integrated optics will have to deliver solutions which use less space and allow simple layouts.

As with other fields in astronomy, interferometry will also gain in new detector technology. For most applications with no inherent field of view, only small area detectors are needed. Detectors with inherent spectral resolution as in superconducting tunnel junctions would also be of help for the photon starved interferometers.

The current implementation of interferometers leads to a limited field of view, which has the size of an Airy disk as defined by the largest telescope used in the array. Accordingly, the field of view gets smaller on larger telescopes. There are three possible solutions for this problem. Optical interferometers have to exploit the mosaicing technique as used in today's radio interferometry. Alternatively one can implement homothetic mapping (Beckers, 1990) or a hypertelescope with a densified pupil (Pedretti et al., 2000). The first concept requires very complex optomechanics. The latter method results in images that have different angular scales superimposed.

The nulling technique has to be developed beyond the laboratory stage, where the deepest nulls have been achieved with lasers and at optical wavelengths.

Phase referencing techniques require highly sophisticated technology. It has to be shown that all the subcomponents can be controlled to routinely deliver science.

Although fringe sensing and adaptive optics have a similar underlying principle, there is no equivalent to an artificial guide star. If someone could produce a method which overcomes this obstacle, the door to faint science with interferometers would be wide open.

Finally, the new generation of interferometers has to deliver the science that has been advertised over the last decade.

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References

Angel, J.R.P.: 2002, Why optical interferometers should have moving elements, ideally two big ones. *Proc. of the SPIE* **4838**(#17), 2002.

Ballester, P., A.M. Chavan, B. Cotton et al.: 2001, Data flow system for the Very Large Telescope Interferometer. *Proc. of the SPIE* **4477**, 225.

Beckers, J.M.: 1990, The VLT interferometer. III – Factors affecting wide field-of-view operation. *Proc. of the SPIE* **1236**, 379.

Berger, J.P., P. Haguenauer, P. Kern et al.: 2001, Integrated optics for astronomical interferometry. IV. First measurements of stars. *A&A* **376**, L31.

Boden, A.F.: 2002, The Keck Interferometer. *these proceedings*.

Coude du Foresto, V., G. Maze and S. Ridgway: 1993, Stellar interferometry with infrared single-mode fibers. *ASP Conf. Ser.* **37**, 285.

Danchi, W.C., C.H. Townes, W. Fitelson et al.: 2002, Status and progress on the upgraded infrared spatial interferometer. *Proc. of the SPIE* **4838**(#05).

Ferrari, M., G.R. Lemaitre, S.P. Mazzanti et al.: 2002, Variable curvature mirrors: implementation in the VLTI delay lines. *Proc. of the SPIE* **4838**(#39).

Froehly, C.: 1982, Coherence and interferometry through optical fibers. *Proc. ESO Conf., Science Importance of High Angular Resolution at Infrared and Optical Wavelengths* **285**.

Glindemann, A., J. Argomedo, R. Amestica et al.: 2002, The VLTI Interferometer – a status report. *these proceedings*.

Hanbury Brown, R., J. Davis and L.R. Allen: 1967, The stellar interferometer at Narrabri Observatory. I. A description of the instrument and the observational procedure. *Monthly Notices of the Royal Astronomical Society* **137**, 375.

Haniff, C.A., J.E. Baldwin, A.G. Basden et al.: 2002, Progress at COAST 2000-2002. *Proc. of the SPIE* **4838**(#03).

Herbst, T.: 2002, Interferometry with the Large Binocular Telescope. *these proceedings*.

Labeyrie, A.: 1975 Interference fringes obtained on VEGA with two optical telescopes. *ApJ* **196**, L71.

Lane, B.F., M. Colavita and A.F. Boden: 2002, PTI status report. *Proc. of the SPIE* **4838**(#08).

Malbet, F., P. Kern, I. Schanen-Duport et al.: 1999, Integrated optics for astronomical interferometry. I. Concept and astronomical applications. *A&AS* **138**, 135.

Meisner, J.A. and R.S. le Poole: 2002, Dispersion affecting the VLTI and 10 micron interferometry using MIDI. *Proc. of the SPIE* **4838**(#126).

Mourard, D., D. Bonneau, P. Stee et al.: 2002, Status report on the GI2T interferometer. *Proc. of the SPIE* **4838**(#02).

Mozurkewich, D., D.J. Hutter and J.A. Benson: 2002, NPOI progress report. *Proc. of the SPIE* **4838**(#07).

Nishikawa, J.: 2002, Status report on Mitaka optical and infrared array (MIRA-1.2). *Proc. of the SPIE* **4838**(#12).

Pedretti, E., A. Labeyrie, L. Arnold et al.: 2000, First images on the sky from a hyper telescope. *A&AS* **147**, 285.

Perrin, G., O. Lai, J. Woillez et al.: 2002, OHANA: the Optical Hawaiian Array for nanoradian astronomy on top of Mauna Kea. *Proc. of the SPIE* **4838**(#15).

Quirrenbach, A.: 2001, Optical Interferometry. *Annual Review of Astronomy and Astrophysics* **39**, 353–401.

Shao, M. and M.M. Colavita: 1992, Long-baseline optical and infrared stellar interferometry. *Annual Review of Astronomy and Astrophysics* **30**, 457–498.

Tango, W.J.: 2002, Status of the SUSI program. *Proc. of the SPIE* **4838**(#04).

ten Brummelaar, T.A.: 2002, Update on the CHARA array. *Proc. of the SPIE* **4838**(#09).

Traub, W.A.: 2002, Recent progress at IOTA with 3 telescopes. *Proc. of the SPIE* **4838**(#06).