Science with the AO-assisted VLT Interferometer

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Abstract

The present status of VLTI is briefly reviewed with emphasis on the scientific objectives that can be expected to be reached in the near future with sophisticated AO compensation. It is shown that, if everything goes according to plan, extensive capabilities will be available to the astronomical community by early in the next century. This will allow very sensitive observations in the near and thermal IR of the outer structure of accretion and debris disks around pre- and main sequence stars within a few hundred parsecs of the Sun, the circumstellar environment of AGB stars out to several kiloparsecs and the inner regions of our galactic center and nearby AGNs. High precision narrow angle astrometry available a little later should also allow detection of low mass companions to nearby stars down to ~ 10 Earth masses and precise phase-referenced imaging should even permit direct detection of massive or young planets and brown dwarfs identified by radial velocity techniques or wide field surveys. Thus, the VLTI will represent a powerful and versatile new facility whose scientific and technical achievements will contribute significantly to 21st century astronomy.

1. Introduction

It was not too long ago that the argument was very cogently made that an array of large telescopes such as ESO's VLTI were not efficient as practical high resolution instruments and that interferometry was only seen as a political justification for arrays of large telescopes rather than as a scientific driver (Dyck and Kibblewhite, 1986, PASP, 98, 260). This argument was based on the correct assumption, at the time, that, since observations could only be carried out in multi-speckle mode in the NIR, the S/N ratio would increase with telescope diameter D only as $D^{1/6}$ (Roddier and Lena, 1984, J. Optics (Paris), 15, 171) thereby basically negating any particular advantage of a large telescope array over one with small telescopes of diameter close to the NIR coherence length of ~ 1 meter or so. Of course, we now know that AO allows us to operate in single-speckle mode for which the S/N ratio increases at a healthy D^2 pace that easily justifies operating an interferometric array with very large telescopes. In this paper, I briefly describe ESO's plans for building an AO assisted VLT interferometer that will bring these concepts to practical fruition in the next decade.

2. The VLT Interferometer

The basic concept consists in the coherent combination of up to four 8m telescopes (UTs) supplemented by a number of smaller 1.8m diameter telescopes (ATs) that can be moved to ~ 30 stations (see Mariotti et al., 1998, SPIE, 3350, 800 and other papers in these proceedings for a complete description). The delay line tunnel at the center of the mountain has room to accommodate up to eight 60m stroke delay lines while the interferometric lab at the center supports the image or pupil plane beam combination instrumentation.

Specifically, in the earliest phases of implementation of VLTI, two UTs will be equipped with Coudé trains and two delay lines installed in the tunnel together with the control system, fringe sensor, image stabiliser and pupil plane beam combiner with the goal of detecting first fringes at $\sim 10\,\mu$. In parallel, two ATs will be developed and installed on Paranal so that interferometry with any combination of 2 UTs and 2 ATs yielding reasonable (u,v) plane coverage will be available for routine operations at 2–10$\,\mu$. Early operations will be restricted to those wavelength regions where the telescopes are essentially diffraction limited and a simple tip-tilt compensation device sufficient for efficient operations i.e. the 10–20$\,\mu$ region for the UTs and the near IR for the ATs.

When the Coudé train adaptive optics (AO) systems will become available, operation of all five telescopes together at $2\,\mu$ will finally be possible exploiting the full capabilities of the VLTI facility where the advantage of ground over space-based interferometers reaches a prominent maximum. Budgets permitting, the next phases would consist of bringing on line the other two UTs, a third AT, and two more delay lines. The basic capabilities of the VLTI in these various modes are summarized in the following paragraphs.

- Availability

The ATs will be used all of the time for interferometry. The observing time for which UTs will be introduced into the VLTI depends solely on the quality of observing proposals, as UT time with VLTI will follow the normal award process.

- Array configuration and UV coverage

Baselines between UTs range from $\sim$ 30m (UT2 and UT3) to $\sim$ 130m (UT1 and UT4). Baselines are shorter (and the coverage thinner) in the NWSE direction. Baselines between ATs range from 8m in the SW corner to 200m in the NS direction. The station layout is very flexible, virtually any desired configuration of three or four ATs can be obtained. Some stations have been placed in such a way that the limited UV coverage of the UTs can be complemented with baselines between a UT and an AT ("hybrid mode"), to result in an even and circular coverage. All telescope/station centers are located on an 8m $\times$ 8m grid.

- Sky coverage

The sky coverage is limited by the sky coverage of the telescopes and the optical delay that the delay lines can produce. All telescopes support a coverage of 60 degrees from Zenith with full performance. The delay lines support a coverage of 60 degrees from Zenith for baselines up to 130m (i.e., all UT baselines). For AT configurations with baselines $>$ 120m, the coverage is reduced and depends on the exact configuration. A good value to use here is 30 degrees. Ultimately, the sky coverage can be increased to 60 degrees on all baselines.

- Field of view

A dual feed capability was recently introduced into the VLTI concepts. The dual feed will support two field angles which may be up to $60''$ in separation. There will be a $2''$ continuous field diameter centered at each of the two field positions. Atmospheric effects introduce differential phase errors between the two conditions at Paranal, a reduction of fringe contrast by a factor 0.7 occurs for field separations of $10''$ at $2.2\,\mu$ wavelengths, and of $40''$ at $10\,\mu$.

- Limiting magnitudes

The sensitivity of VLTI depends critically not only on the brightness, but also on the structure of the source. The main point to notice in the context of this conference, however, is the enormous gain in sensitivity that will follow directly from equipping each UT Coudé train with an AO capability. The following table gives a summary for simple, point-like sources:

EXPECTED SENSITIVITY				
Array Mode	Tracking Mode	V Band (0.55 mic)	K Band (2.2 mic)	N Band (10 mic)
VISA	self WFS (self FT)	13 (11.4)	9 (12.8)	5 (5.5)
	other WFS, self FT	13	13	5
	other WFS, other FT	22	20	9
VIMA / Hybrid	self WFS (self FT)	13 (11.4)	9 (12.8)	8 (8.1)
	other WFS, self FT	16	16	8
	other WFS, other FT	25	23	12
VIMA / Hybrid	blind operation	20 (19.6)	20 (15.3)	10 (10.6)

Assumptions: point source (100% visibility), use full spectral band, observing time 600 sec, SNR=10, seeing 0.75 arcsec

Legend: self WFS/FT: tip-tilt or adaptive optics/fringe tracking on program object at the same wavelength

other WFS/FT: tip-tilt or adaptive optics/fringe tracking on reference object or program object at the same wavelength

- Notes to the table

- "VISA" mode uses only 1.8m ATs.
- "VIMA" and hybrid use 8m UTs only and UTs+ATs.

- Tracking modes

- self WFS, self FT: the program source is used both for wave-front sensing (WFS) for the adaptive optics and for fringe tracking at the observed wavelength. The magnitude is essentially limited by the adaptive optics limiting magnitude.
- other WFS, self FT: a reference source within the isoplanicity patch ($< 10''$ in V; $< 30''$ in K; $< 60''$ in N) sharpens the program source image. Program source light is used for fringe tracking. Magnitude limit is due to fringe tracking.
- other WFS, other FT: reference source used for both AO and fringe tracking. Limiting magnitude is due to integration time and SNR. This case will be subject to the isoplanicity limits.

- Blind operations

No reference source is used. The delay lines track the expected geometric delay, i.e., a model for the instrumental delays and telescope positions is used to control the delay time positions. Short exposure interferograms are taken. Those will show fringes only if the deviation from zero path difference is small ($\sim 3\,\mu$ in V, $10\,\mu$ in K, $50\,\mu$ in N). Atmospheric piston will produce path differences of 10–30$\,\mu$ rms. Feasible only when the instrumental characteristics of VLTI are very well known.

- Instrumental capabilities

Preliminary design of the following three focal plane instruments meeting the stringent scientific requirements of VLTI has been accomplished by consortia of European institutes:

1) A mid-IR interferometric instrument to operate in the 8–13 μ wavelength band with three to six baselines (MIDI). An initial version will make fringe amplitude measurements only while a later extension will provide for phase measurements and imaging. Accurate phtometry will be accomplished by chopping on the sky to normalize the fringe amplitude. Moderately accurate metrology will be required for external fringe stabilization. Low spectral resolution 0f ~ 100 is planned.

2) A near IR closure phase instrument operating in the 1–2.5 μ band (AMBER). This instrument will be the only one offering imaging capabilities with a 3-way beam combiner over a field of view varying from an Airy disk ($\sim 0.06''$ and $0.25''$" at $2\,\mu$ for the UTs and ATs respectively) to calibration and spectral resolutions up to 10000 will be special features of this instrument. Expansion to low order adaptive optics compensation is expected.

3) An instrument for phase-referenced imaging and microarcsecond astrometry (PRIMA). This instrument will operate in the K band only to carry out narrow angle astrometry of 2 stars within the isoplanatic patch with 10 microarcsecond accuracy and imaging of faint objects with a dynamic range of 100 or better. It will use high precision 5nm differential metrology and $50\,\mu$ baseline vector calibration. Variable spectral resolutions up to 3000 are planned.

3. Scientific Applications

It is expected that the AO assisted VLTI will contribute significantly and uniquely to a number of important areas of present and future astrophysical research. Of these various worthy objectives (see Science with the VLTI, ed. F. Paresce, Springer, 1997 for a complete list and descriptions) four are particularly crucial in the next decade, i.e.: 1) detect and characterize objects of mass $\lesssim 0.2$ solar masses in order to determine the luminosity and mass function of stellar and substellar populations of different ages and composition, 2) image the circumstellar environment in nearby star forming regions in order to understand the basic stellar and planetary formation mechanisms, 3) probe the center of our galaxy to establish the presence or absence of a central massive black hole and 4) probe the central regions of nearby AGNs in order to test the unified model. These programs form the core scientific objectives that drive the technical requirements for the VLTI. In the following paragraphs, some of the planned ground-based capabilities in these areas that are most relevant to a direct comparison with the expected performance of future space-based devices are briefly summarized.

Little is known presently about the stellar and substellar mass and luminosity functions of objects of mass $\lesssim 0.2$ solar masses although radial velocity (RV) and microlensing surveys are starting to fill in the gap in the near future. The accurate determination of the mass and luminosity of red dwarf stars near the Hydrogen burning limit, brown dwarfs, and planets in different environments and stages of stellar evolution will be a critical objective in the next decade. For this, it will be necessary to cover a range of several decades in mass and distances extending out to at least r ~ 500 pcs. The latter range is such that it would include a large number of stars of different spectral types and luminosity classes and of young and old open clusters and star forming regions of different ages and metallicity.

Many of these objectives can be met, in principle, by accurate narrow angle astrometry (NAA) carried out over a period of time to determine the precise orbits of low mass companions to main sequence (MS) and PMS stars. The ultimate accuracy achievable with this technique has been estimated to be ~ 10 microarcseconds. The RV method is especially sensitive to the $\sin i$ uncertainty while the NAA suffers from uncertainties in the proper motion of the reference stars. Except in the case of double-lined spectroscopic binaries, both methods are subject to errors in the mass of the primary. On average, we should expect to achieve $\sim 4\%$ relative precision in the mass of the companion of a large number of stars in the solar vicinity. Gas giant cores at 5 AU could be detected at this accuracy level provided they are located around 1 or 0.1 solar mass stars not much farther than ~ 10 or ~ 100 pc, respectively. Earth-mass planets need to be orbiting very nearby M dwarfs for them to impart a detectable wobble to the primary.

It should be emphasized that there is an exciting area waiting to be covered around the Hydrogen burning limit where the mass function is very poorly determined if at all and which can be readily accessed even by relatively modest position accuracies of 100–500 microarcseconds. One should also keep in mind that NAA techniques will allow coverage of objects that cannot be measured accurately by the RV method because the primary star's spectrum is unsuitable. These include many PMS and early type stars whose emission lines are scarce and broad.

Since only indirect information on the object's luminosity can be obtained by either of these methods, however, the VLTI will be essential in order to carry out a more detailed study of suitable candidates by directly detecting the low mass companion. Although this is an ambitious goal, the technology is definitely within reach. The possibility exists to detect and measure the intrinsic broad-band thermal IR luminosity of a faint companion to a bright star corresponding to an intrinsic $\sim 10^4$ contrast ratio at 10–20 μ. Low to medium resolution spectroscopy to obtain the object's SED in the IR should also be feasible. This dynamic range is compatible with the expected contrast ratio of a Jupiter-like planet orbiting around a solar type star at separations of order 1–2 AU or with younger and hotter planets that may be orbiting young stars in the nearest star forming regions provided the observations are carried out in the N or Q bands.

The essential ingredient in both the stellar and planetary formation mechanisms is expected to be the accretion disk. The prototypical disk can probably only be viewed through severe extinction in the most favorable conditions. The size of the observable disk increases with wavelength much faster than the spatial resolution decreases, however, so that observations in the thermal IR are particularly useful. As time progresses in its evolution towards the MS, the stellar photosphere and halo are slowly cleared by radiation pressure and P-R drag and the remnant of a disk should become easier to see in the near IR as is the case, for example, for the MS IR excess stars. At this point, the disk may extend out to several hundred AU but be detached from the star by a few AU.

Accurate imaging of these disks will clearly require the triple combination of high sensitivity, resolution, and dust penetrating ability of an IR optimized AO-assisted VLTI. For the closest star forming regions located at ~ 150 pcs, the accretion disk will be $\lesssim 100$ mas in extent and require spatial resolutions in the range 1–20 mas for accurate mapping of its outer portions. These spatial resolutions will be sufficient, for example, in detecting gaps or flaring that are very sensitive indicators of the presence of low mass companions such as planets. Spectral resolutions from a few for high sensitivity to dusty featureless disks to several thousand for kinematic studies of the inner disk, wind and jet features should be straightforward.

The study of the IR excess MS stars that have large dusty disks surrounding them also requires observations in the thermal IR where their emission peaks and their temperature structure can be determined most unambiguously. The latter is the critical observational parameter needed to constrain the accretion disk models presently available. At the same time, for an understanding of the later stages of PMS evolution and, in particular,the circumstellar envelope, the wind and the jets, high spatial and spectral resolution in the NIR will be of fundamental importance.

The VLTI's IR sensitivity and angular resolution are sufficient to resolve the central region of our galaxy since 10 mas would correspond to ~ 100 AU at the galactic center. The targets that will certainly be attacked first with this device will be the star cluster centered on IRS 16 and the infrared sources close to the position of SgrA*. It is expected that the 3D velocity field of the cluster could be determined all the way in to the core where single telescopes would be limited by crowding. This information, together with the continuum spectrum of every object therein, will shed considerable and, perhaps, definitive light on the nature of our galaxy's center including, in particular, whether or not it harbors a massive black hole and whether or not there is local and continuing star forming activity. The spectra will also be searched for signs of a possible collapse of the cluster core and the role of binary star formation due to an enhanced collision rate. Finally, good (u,v) plane coverage should also ensure the capability of imaging directly in the IR an accretion disk surrounding the black hole and to reveal the distribution of warm dust associated with SgrA*.

The central one parsec or so will certainly be probed in about 20–30 nearby Seyfert galaxies that are bright enough to be used as references for fringe tracking. These measurements are quite likely to answer some of the basic questions concerning AGNs like whether the observed differences are due to evolution, environment or viewing geometry. Detailed imaging of the obscuring torus of dust and gas is certainly the best way to directly investigate the unified model of AGNs.

4. Conclusion

Adaptive optics consisting basically of a deformable mirror at the telescope pupil at M8 and a wavefront sensor on an x-y translation stage located at the f/47.3 Coudé focus of the individual UTs will bring the VLTI to its full scientific potential. A dual beam capability to use a reference star within a $2'$ diameter field of view will, moreover, permit giant steps in both sensitivity and field coverage. Practically all the critical science objectives will then be met and probably exceeded. It is not unreasonable to predict that sometime in the first part of the next century, the VLT time allocation will consist of more than 80% of the total time reserved for VLTI operations.