Astrophysical drivers for the VLT/NAOS

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Abstract – The Nasmyth Adaptive Optics System (NAOS) on the VLT will provide diffraction limited images over a wide wavelength domain and high Strehl ratio in the near to thermal IR domain. We present here an overview of the scientific drivers of Adaptive Optics Systems on large telescopes, as well as the expected performances of NAOS, and discuss their impact on science.

1 Introduction:

Adaptive optics (AO) on 4-m class telescopes is now routinely used. The obtained diffraction limited images have already allowed new insights in many fields, in particular planetary science, stellar astrophysics, and sofar to a minor extent, in extragalactical domain as well (Ridgway, 1998). Results obtained with AO can be found in this volume or in Lagrange, Mourard and Léna (1997) and Stecklum (1998).

The systems currently developed for the 10-meter class telescopes will allow to expect better performances in terms of Strehl Ratio (SR) and ability to use fainter objects as reference sources. The consequences on science are huge.

We briefly describe in section II the astrophysical issues and their implications on the design of adaptive optics systems. Section III will briefly present the NAOS system as well as the spectro-imager CONICA, and section IV will present the expected performances and capabilities of NAOS.

2 Astrophysical issues and instrumental implications:

Almost all astronomical domains can benefit from the use of AO on large telescopes.

2.1 Solar System:

2.1.1 Astrophysical issues:

Obvious programs are the Solar System planets themselves, in continuation with the works already made with AO on 4-m class telescopes on their morphology and activity. For a detailed review, see Encrenaz (1997). The latter

emphasizes the gain that will be achieved on 10-m class telescopes, and also the need not only for imaging, but also for near IR to thermal IR spectroscopy for the study of planet atmospheres. The planets studies (morphology, activity, chemical contents; physical processes) are fundamental to understand their formation and evolution.
Other and smaller bodies may be observed with AO:

- asteroids: the largest asteroids in the asteroids belt are large enough to be resolved with AO on large telescopes, with a linear resolution of about 100 km at their surface, at a distance of 3 AU. AO on 4-m telescopes enabled to observe the very largest ones (Saint Pé et al, 1993; Hainaut et al 1994, Encrenaz, 1997). Thermal and physical properties of these objects can be constrained. Near Earth asteroids NEAs are smaller bodies (typ. 1km) that graze the Earth. These objects could be resolved at a linear resolution of about 100m; both their shape and spins could be determined. The study of these bodies is important to understand their dynamical history, and give informations on the evolution of our Solar System.

- comets : distant comets (typ. 5 AU) can be observed to study their chemical composition and survey their activity on small angular scales. Spectroscopy is usually needed. Nearby comets which pass very close to the Earth (e.g. Hyakutake in 1995) may be resolved and chemically studied (Marco et al, 1996 for AO observations of Hyakutake). Near IR to thermal spectroscopy is obviously needed.

- Trans Neptunian Objects (TNO): to explain the origin of short period comets, a reservoir of material beyond the orbit of Neptune (Kuiper belt) has to be present. These very small objects (typ. 100km) at 35 AU from Earth (Hainaut, 1994; Jewitt and Lu, 1993) are very interesting to understand the processus of Solar System building. A few tens of them are known to this day, but many more exist and can be detected and studied (albedo, activity). These objects are faint ($V \geq 21$) and require a close bright star for wavefront sensing. Hainaut et al (1994) have shown that each TNO is close to one or two stars every year; hence the probablity of such events is about 1-2/week with the currently known TNOs.

- planet satellites can be studied (activity, climate, mineralogy). AO imaging as well as near IR to thermal spectroscopy on the VLT is expected to bring significant progress in the knowledge of Io and Titan. Also, faint satellites can be discovered (cf satellites of Saturn in 1995 observed with Adonis and HST).

2.1.2 Implications for the AO instruments:

Ability to use extended objects as reference sources:
The references may be the planets themselves or satellites, depending on their size (see table 2.1.2). This size has to be taken into account in the design of the AO systems. Mercury, Venus, Mars, Saturn and Jupiter are very large and can not be used for WF sensing. Asteroids and satellites have smaller sizes (≤ 1.5"). Uranus (J=8.2/arcsec^2) is 3.5" and Neptune 2.2" (J=9.4/arcsec^2).

Object	Angular diam. (")	Object	Angular diam. (")
Mercury	11.6	Triton	0.12
Venus	62	Pluto	0.08
Moon	1900	Ceres	0.7
Mars	18	Typical asteroids	0.06
Jupiter	50	Typical comet	0.013
Io	1.0	(at 1 AU)	
Saturn	20	Typical comet	0.0003
Titan	0.8	(at 5 AU)	
Uranus	3.7	Typical TNO	0.004
Neptune	2.3		

Table 1: Parameters of planets, satellites and large bodies in the SS. Angular sizes are given at opposition for outer planets and lower conjonction for inner planets.

Ability to follow the motion of the objects:
Planets:
Only Pluto, Uranus and Neptune are concerned. Their proper motions are smaller than those of satellites (see

below).
Satellites:
To observe large planets (e.g. Saturn and Jupiter), one generally uses their satellites as reference sources for WF sensing. Two effects can degrade the image quality:

- the rotation of the planet itself. Typical values for the rotation are 0.1" in t $\simeq$ 10 sec/cos(θ) for Jupiter and 20 sec/cos(θ) for Saturn, where θ is the latitude.
- the motion of the satellite with respect to the planet: for instance, the maximal relative velocity of Jupiter satellites is 20"/hour (i.e. 5.5 mas/sec)

Due to the rotation of the planet, the exposure times have to be short (typically a few seconds) if one wishes the best angular resolution. However, within these few seconds, the motion of the satellite with respect to the planet is still large enough to degrade the image quality.
Comets:
To observe comets (extended objects), one may use background stars, depending on the size of the coma. In that case, the motion of the comet relative to the background star is a cause of image degradation. This is especially true for comets with short perihelia (e.g. Hyakutake). Typical values of absolute velocities follow:

- maximum absolute velocity at Jupiter distance: 6"/hour
- maximum absolute velocity at Mars distance: 50"/hour

TNO:
These objects have low proper motions: 2"/hour which is far less constraining than comets or satellites.
Observing modes:
Various observing modes are required to study these objects:

- BB as well as NB imaging (study of the mineralogy of the surfaces) both in the near IR (CO, H2) and thermal IR (H3+, CO_2),
- mosaicing to map surfaces, up to 40" (Jupiter),
- spectroscopy (R$\geq$ 1000) in the near and thermal IR to study the chemical composition of the gaseous phase.

2.2 Young stars:

2.2.1 Astrophysical issues:

It is anticipated that a lot will be learnt from high angular resolution (HAR) observations of young stellar objects (YSO), especially about their close circumstellar (CS) environment: accretion disks, base of the collimated jets, companion... These observations will provide invaluable new information on the way stellar systems form and evolve. AO observations on 4-m class telescopes already enabled the detection of the outer parts of a few circumbinary disks (Close et al, 1997, 1998; Roddier et al. 1998). The turbulent structures of jets have also been resolved. AO on the VLT will enable to observe at higher resolution and higher contrast these extended structures. The challenge will be to try and observe the innermost parts of these disks to understand the accretion process and also to observe the very base of the collimated jets to identify their driving mechanism(s) and intrinsic dynamics.

The closest T-Tauri (TT) stars are located 130 pc away and typical accretion disk sizes are of order 150 AU in radius. Their outer parts however are very faint. Thermal emisson in the NIR is confined to the central 0.1 AU and only faint scattered light is detected far from the source. Access to high contrast and high resolution is crucial. A resolution of 0.06" will give unpreceedent views on the accretion disks/collimated jets of the nearest TT stars. Polarization should help determining the grain properties.

Also important is the issue of multiplicity which seems much more common in YSO than on the main sequence. In the past years, it has indeed been observed that a large fraction of stars ($\geq$ 50%, and maybe up to 100%) in the Taurus, Ophiuchus and Orion clouds are multiple (Ghez et al. 1993; Reipurth and Zinnecker, 1993). Similar results were found in older clusters like the Pleiades (Bouvier et al. 1998). Important questions are now 1) whether stars tend to form in multiple systems and separate afterwards, which means that there is a link between multiplicity and

PMS evolution (e.g. Ghez et al. 1993), 2) multiplicity rates depend on initial conditions and change from cloud to cloud. An obvious way to answer these questions is to study the multiplicity in other, more remote, star forming regions (e.g. Perseus). This can be achieved easily with AO on large telescopes. Also, the gain in angular resolution will enable to detect new multiple systems that are tighter and have a larger contrast, even in the complexes that have been surveyed before. This will broaden the separation range investigated by the observations and will allow to check whether the separation distribution is continuous or not. In the study of multiple systems, an important issue is the characterization of the companions. The 1-5 μm region is particularly well suited as the SEDs of TTs peak in that region. Color informations between 1 and 5 μm are therefore very important to get (see for example Monin and Geoffray, 1997).

An important subject in today's astrophysics is the detection of brown dwarfs (BD). BDs ($M \leq 0.08 M_{\odot}$) are potential explanations for the missing mass in the Universe; they are also of intrinsic interest as their atmospheres differ from those of planets and stars. They can be searched for either isolated, e.g. with EROS and MACHOS surveys (Aldock et al; Aubourg et al, 1993) and DENIS survey (Delfosse, 1997) or associated to stars. In that case, direct informations can be obtained on their mass as their orbit may be determined.

BDs have been searched for around close MS stars (see next section). Young stars are potentially very good sites to look for BDs, as the luminosity ratio between the star and the BD is much more favorable than in the case of older stars (Allard and Hauschild, 1995; Brandner et al, 1997). As PMS stars are located far away, HAR with very good Sr is definitely needed for this kind of search. AO on the VLT could enable to detect BDs orbiting PMS stars at 150 pc down to 9 AU separation.

2.2.2 Implications for the AO system:

Quality of correction:
The best quality correction (best Sr) is needed for studies of close multiple systems.
Mosaicing:
Some observations may require large fields of view (1') and hence mosaicing facilities.
Need for IR WFS:
Some sources, especially the very young ones, are still embedded in their parent cloud or in very absorbed regions (V-K $\geq$5); their optical counterpart is then very faint whereas they are bright at IR wavelengths. Hence, an IR WFS is needed for these objects. As an example, the measured number of sources over 1 square deg. around the Kleinman Low nebula star forming region with V-K $\geq$ 6 and K $\leq$ 12 is already as high as 500 (Copet, 1997). Most of these objects are likely to belong to the clusters of stars very recently born in the core of molecular clouds. They are therefore very important to study the early phases of stellar formation.
Observing modes:
Various observing modes are needed: spectroscopy, polarization, coronography.

2.3 Stellar companions, disks and planets around MS stars

2.3.1 Astrophysical issues

The first BDs associated to stars have been discovered in coronographic, tip-tilt corrected images (Nakajima et al, 1994). The high luminosity contrast between the BD and the parent star requires indeed the use of coronographs to block out the star's light. Many surveys with AO on 4-m telescopes are underway to detect other BDs, in particular with ADONIS and PUEO. Their temperature ($\simeq$ 2000K) suggests that the best wavelength range to observe them is the near IR. AO on large telescopes will help finding other BDs around more remote objects, but also fainter companions closer to nearby stars. Further studies of BDs includes their spectroscopic analyzes (Allard et al, 1995) in the near IR where molecular hydrogen and methane bands can be searched for.

CS disks around MS stars are now known to exist, as revealed by IRAS measurements of IR excesses, and a few cases (β Pictoris, BD +31643, HR 4796, 55 Cnc), as shown by direct coronographic images of the light scattered by the dust. Such disks are important since they provide clues to the formation and evolution of planetary systems. Whereas classical observations of β Pictoris enabled to observe its CS disk down to typically 80 AU from the star, ADONIS coronographic and HST observations allowed to detect it down to about 20 AU, i.e. inside the planet orbits in our Solar System (Burrows, 1995; Mouillet et al, 1997a), and find indirect informations on the presence of planets (Mouillet et al, 1997b). Coronographic AO images on large telescopes should enable to detect many more disks, and also to study them in greater details. In particular, thanks to the gain in angular resolution, gaps due to planets could be detected, if the image quality is good enough.

Extrasolar planets cannot be directly found with classical AO imaging or even with classical coronographic AO imaging. Angel (1994) has suggested to use ultra performant AO systems to directly detect outer planets. This is beyond the possibilities of presently developed AO systems. Other potential ways are to use achromatic interferential coronographs (Gay et al, 1997) or the dark speckles in AO coronographic imaging (Labeyrie, 1995). Simulations show that this could be done with foreseen AO systems on 10-m class telescopes (Boccaletti et al, 1997), but needs rapid read-out and very low RON detectors.

2.3.2 Implications for the AO system:

Quality of correction:
The best candidates for detailed studies of disks or search for BDs close to stars are usually bright objects ($V \leq 13$). For such studies, the best AO correction is required, in order to use coronographic focal masks as small as possible. Indeed, not only the PSFs should be diffraction limited, but the halo should be as faint as possible to ensure the best rejection rates. For instance, the β Pictoris disk is about 12 mag/arcsec^2 at 1.5" from the 3.8 magnitude central star.
Observing modes:
As seen, coronography is mandatory (disks and faint companions) and spectroscopy needed (BD atmospheres).
Observations in the visible domain:
Also, and very importantly, observations in the visible domain are required to image giant extra solar planets or low mass BDs with dedicated techniques coupled with AO, and well suited to detect CS disks.

2.4 Stellar populations in the Galaxy:

2.4.1 Astrophysical issues:

Globular clusters are very important targets since they contain the oldest populations of stars. HAR is critical for a detailed study of these dense (10^6 stars/pc^3) and remote (d$\geq$ 3-4 kpc; typical distance 10 kpc) objects in our Galaxy, as shown by recent HST results. Many physical processes may be studied (core collapse, oscillations, mass distribution, stellar contents, star ejections and interactions (e.g. blue stragglers; Weaver et al, 1997)). To study the lower mass stars, IR observations are better than visible ones. Color informations are needed and therewere an access to thermal and visible domain is needed. Spectroscopy may be used to sense the binary contents in globular clusters (Butler et al, 1997) and the global motions of the stars.
The initial mass function is an important problem in today astrophysics. Its determination requires the observations of very low mass stars(≤ 0.3 M$_\odot$), down to the limit of Hydrogen burning (0.08 M$_\odot$) on the one hand, and of most massive objects on the other. For the latter, the best angular resolution is needed to possibly avoid observational artifacts due to limited angular resolution (Heydari et al, 1994). The very low mass stars are also important to study the stellar formation mechanisms (e.g. multiplicity).

2.4.2 Implications for the AO system:

Quality correction:
The main implication for these types of targets is the quality of the correction in order to achieve the best angular resolution and resolve very close objects with various luminosities.
IR WFS:
The study of very low mass stars, hence very red objects (V-K =3.5 for M0V stars), requires the use of an IR WFS.
Observing modes:
Various observing modes are needed, in particular mosaicing over large fields (1' or more).
Need for WF sensing on faint objects:
Depending on the clusters, a laser guide star (LGS) may or may not be needed.

2.5 Post MS stars:

2.5.1 Astrophysical issues:

In order to test the theories of post MS evolution and the physical processes involved (e.g. mass loss) one has to observe the environment around these stars on large but also small spatial scales. HAR imaging is hence needed. As mass loss depends on the star luminosity and temperature, the geometry and chemical composition of the CS material will change depending on the studied stars. Access to narrow band imaging or spectroscopy is also needed. For a detailed review of this question, see Paresce (1997).

Massive stars:

Massive stars (blue giants) are surrounded by hot bubbles or cavities of ionized gas within a thin shell of wind and ISM, at about 20-30 pcs.

Supernovae events lead to complex structures as illustrated by HST observations of SN1987A (Sonneborn, 1997). In that case, HAR narrow band imaging enabled to identify the chemical elements (OIII, NII) in the expanding material.

Luminous blue variables (LBV) exhibit phases of large mass loss; the origin of which is still not well understood. Their environments (gas and dust) are complex (e.g. Eta Carinae, P Cyg, AG Car) and their studies requires both spectral (narrow band imaging) and spatial (as good as possible) resolutions (see for instance HST images of AG Car) over large FOV (tens of arcsecs).

Late type stars:

These stars (e.g. IRC 10 216) are also surrounded by large amounts of gas and dust whose origin is still not well understood. In order to understand the underlying physical and chemical processes, one needs to explore the inner part of the dust regions, which requires both spectral and spatial resolutions as well as their more extended counterparts into greater details. Also, winds and jets around Mira variables can be detected at spatial high resolution (scales of a few tens of AU).

2.5.2 Implications for the AO system:

IR WFS:

Envelopes of late type stars may have opacities larger than 100 mag in the visible domain, and are very bright at IR wavelengths. Their observation requires an IR WFS.

Observing modes:

Mosaicing (tens of arcsecs) and spectroscopy are needed.

2.6 Galactic Center:

2.6.1 Astrophysical issues:

A very interesting challenge is to understand the center of our Galaxy. Both the stellar population and interstellar medium dynamics can be studied to constrain the nature and mass distribution in the very center of our Galaxy. This requires of course the highest possible angular resolution to get precise proper motion and radial velocity informations as a function of time. AO observations with 4-m class telescopes as well as HST NICMOS observations have shown the complexity of this region and enabled to start proper motion studies (Davidge et al, 1997a; Rigaut et al, 1998a). AO on larger telescopes will enable to go much deeper, on smaller spatial scales (0.002 pc) and to get spectroscopic informations.

Also, the stellar population in the very center of the Galaxy will be studied with unprecedent details, which will contribute to a better understanding of the history of our Galaxy.

2.6.2 General Implications for the AO system:

IR WFS:

Due to the very high (Av$\simeq$30) dust absorption in this line of sight, observations must be taken in the IR domain. Also, more numerous and brighter reference sources can be found in the IR. Even though observations are possible with visible WFS, e.g. PUEO, an IR WFS will give better Sr. There are indeed 29 sources with K $\leq$ 9.5) detected in the very central (9$\times$9 arcsecs^2) by Eckart et al (1995) and Rigaut et al (1998a) hence the use of IR WFS is

mandatory to achieve the present goal.
Note that this argument is also true for all objects in the galactic plane: due to the high opacity of the galactic plane (1 mag/kpc) distant objects of the Milky Way have very high V-K and require the use of IR WFS to be observed. A few million of them have K $\leq$ 10 (preliminary results of DENIS survey) and are potential candidates for AO/VLT observations.

Observing modes:
Mosaicing and spectroscopy (FP) are needed.

2.7 Detailed studies of nearby galaxies:

2.7.1 Astrophysical issues:

Detailed studies of the morphology and contents in nearby galaxies (LMC, SMC...) can be done at unprecedent angular resolution. In particular, detailed studies of globular clusters can be done (see HST and AO results in M31; Davidge, et al, 1997b). This will help understanding the formation and evolution of globular clusters in various galaxies. Also the stellar population and IMF can be studied, as shown by ADONIS observations (Brandl et al, 1996) in the case of R136.

2.7.2 Implications for the AO system:

For such studies the best Sr are needed. Also, IR color informations is needed and hence an access to the thermal domain. WF sensing on faint objects is also needed.

2.8 Black holes:

2.8.1 Astrophysical issues:

Recent observations, in particular combined HST and Keck observations have showed the presence of massive blackholes in a number of external galaxies (Hutchings et al, 1997). The success of such an approach is due to the combination of the best angular resolution imaging and spectroscopy (FP). It is anticipated that such works will strongly benefit from AO on large telescopes, where spectral and angular resolutions will be available simultaneously, rather than separately.

2.8.2 Implications for the AO system:

For such studies the best possible Sr are needed. Depending on the cases, WFS sensing on faint objects will also be needed. Spectroscopic mode is required, and mosaicing needed.

2.9 Active and starburst galaxies

Adaptive optics will provide HAR images of starburst and active galaxies. The main driver for these studies is to understand the physical processes at work in different classes of objects. Among others, HAR imaging will address the long standing questions of the connection between starbursts and AGNs, or what makes the difference between radio-loud and radio-quiet objects. This will be achieved by detailed studies of nearby objects with correction achieved on the nucleus itself and extended to the highest redshifts providing a bright enough star is present in the vicinity or a LGS is available.
Review paper on the interest of HAR observations for study of AGNs and Starburst activity in central regions of galaxies can be found in Ulrich (1988), De Robertis (1994), Genzel et al. (1995), Rouan (1997).

2.9.1 Astrophysical issues:

AGNs:
The largely accepted unified model of AGN invokes the presence of a thick torus around the central engine, whose inclination on the line of sight would be the key parameter fixing the respective importance of the Narrow Line Region and of the Broad Line Region. The scale of 0.05" translates to d = 5 pc at D = 20 Mpc this means that the NLR is accessible with AO technique for a significant sample of relatively nearby objects.

HAR visible imaging is limited to the mapping of the surface of the cone of photo-ionized gas in [OIII] or other high excitation lines associated to the NLR. The infrared range has the strong advantage of a deeper probing capability through the very opaque dust (Av > 100) predicted around the AGN. Access to the 50 mas domain on a large sample of objects will allow to tackle several questions : nature of the NLR (free-free emission, Br_γ), extension and opacity of the thick torus of gas/dust (H_2, PAH features, hot dust emission), existence of a central massive stellar cluster (FeII, Br_γ, CO lines), etc.. Establishing the 2 μm compactness and resolving the 5 μm region, in order to find the dust temperature distribution $T_d(r,\theta)$, are important to determine the torus morphology and/or a possible warp of the dust disk. Detection of optical counterpart to the extremely collimated radio jets currently observed in active nuclei or radio-galaxies is certainly a goal that HAR will be able to reach routinely in the near future (see e.g. the HST image of the nucleus of the giant elliptical galaxy M87).

Starbursts galaxies:

Starburst regions are patchy and highly obscured with confusing morphology. HAR infrared imaging is best suited to disentangle the different components (old and young stars, nucleus, molecular complexes etc.).

How does the star formation rate vary with gas density (e.g. is there a universal Schmidt law ?) This important question is difficult to explore in the most violent bursts (Ultra Luminous IR Galaxies (ULIRG) : L > $10^{12} L_\odot$) because they are far away (typically 200 Mpc) : ULIRGs require imaging with an angular resolution better than 0.1" in order to reach scales below 100 pc where the starburst activity is concentrated and to separate clearly the nucleus from clusters of very young stars. H^+ lines (Br_α, Br_γ), will trace young hot stars and/or superwind. Mapping fluorescent H_2 at 50 mas resolution in the near-IR, will reveal the thin shocked region in mergers and/or the concentration of hot molecular gas in the nucleus. HAR line-imaging in the PAH bands (3.3 μm) will provide, in addition to the location of the molecular material, an information on the local UV density, by tracing the destruction of those molecules in starburst and superwind.

The propagation of the starburst through chain reaction can be detected in spectro-imaging (e.g. CO line at 2.35 μm tracing supergiants, FeII line at 1.69 μm revealing SNs) that will characterizes the relative age of the different regions. In nearby starburst, the evolution of very young stellar clusters (e.g. R136 in the LMC) with very high stellar densities, is an important field that NAOS, combining spectroscopy and high angular resolution, will open, giving the capability to study the role of collisions, tidal disruptions, stripping of envelopes etc.

Ultra luminous IR galaxies:

These objects (ULIRGs) are potentially very interesting (Sanders & Mirabel 1996) as they are starbursting galaxies often hosting an active nucleus. The fraction of active nucleus (Liners and Seyferts) increases with the infrared luminosity from 35% to 75% at log $L_{IR}/L_\odot$ = 10.5 and 12.5 respectively. They are thus ideal objects for studying the origin of the nuclear activity from high resolution imaging and spectroscopy of the inner part of the galaxies. They are most often mergers; the fraction increases from 12% (separations of the cores of the order of 20 arcsec) to 95% (separation of the order of 2 arcsec or less) at log $L_{IR}/L_\odot$ = 10.5 and 12.5 respectively. These objects are potentially as interesting as normal AGNs.

An important result would be the proof that hidden AGN are deeply embedded in the dust of ULIRGs ; this quest is particularly difficult because of opacities in excess of 100 in those objects: 5 μm HAR imaging is a powerful tool in this respect since resolving the dust emission will be a strong indication that there is no AGN. Understanding how the monster can be fueled with gas is, by itself, a critical problem. Only detailed observations at HAR will allow to discriminate among the proposed mechanisms : a superdense stellar cluster associated to the AGN or micro spiral and bars system inducing the required torque.

The starburst/AGN connection:

The proper separation of the AGN from the starburst is required, in order to assess their respective contributions to the energetics and physical processes. A fundamental question is whether a phase of interaction/merging is always required to obtain an AGN; in this respect, one will look for clues indicating such an event : double nuclei, wisp, tails, etc. Spectroscopy with a good resolving power, allowing dynamical studies of nuclei will become an irreplaceable tool, since dynamically decoupled nuclei, and even counter-rotating ones, are strong indications of the occurrence of a major interaction in the past.

IR luminous galaxies:

An important challenge is to understand the energy generation mechanism powering these infrared-luminous galaxies (massive bursts of star formation versus active galactic nuclei). Observations in the near-infrared are needed with the highest spatial resolution. The images trace the spatial extent of the warm (> 200 K) dust which must lie close to the heating source. Recent observations (Miles et al. 1996) at $\sim$ 10 μm (FWHM $\sim$ 0.6 arcsec) of ten of the brightest galaxies (N-band flux larger than 200 mJy) show complex extended structures within 2 arcsec from the nucleus. Between 20 and 100 % of the light comes from the unresolved component.

2.9.2 Implications for the AO system:

Quality of correction:
The advantage of a high core/halo contrast given by AO is essential, since in many cases the presence of an AGN can dazzle the field. Strehl ratio larger than 40 % are probably required to be able to detect the direct environment of a conventional AGN.

Fig. 1 gives the number of objects brighter than respectively 16 (upper histogram) and 14 (lower histogram) according to their distances: at a limit of $m_V = 16$, 180 objects could be observable, with a resolution of 25 pc or better (134 for $m_V = 14$). In the case of more distant objects, an LGS is required ; in this case, tip-tilt correction

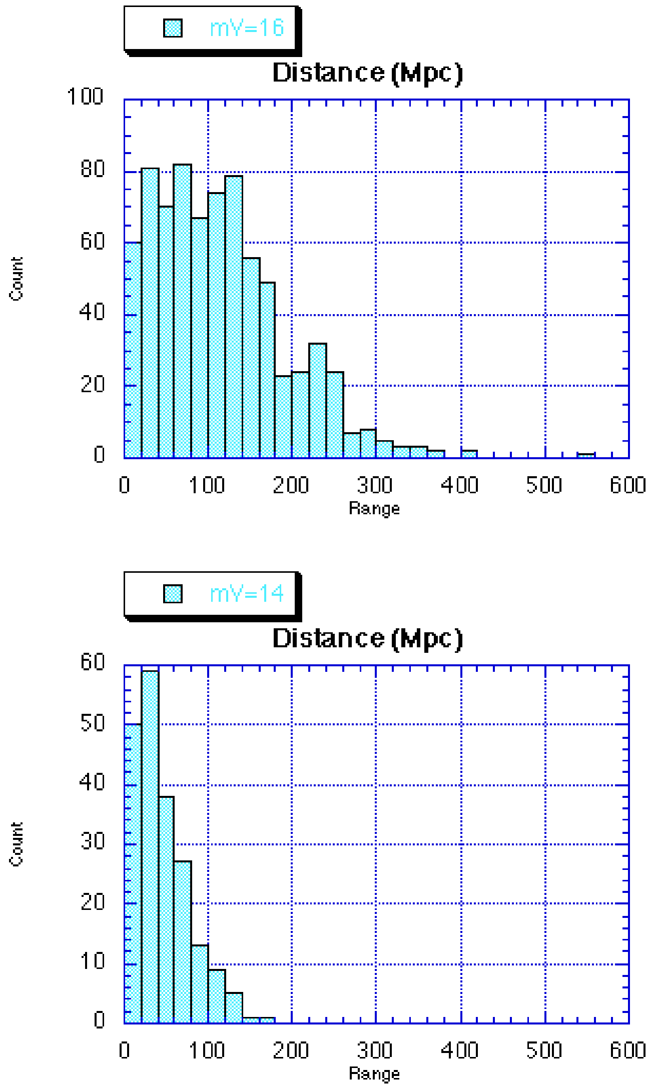


Figure 1: Histograms of number of AGNs (Veron-Cetty, 1996) with mV < 16 and mV < 14 vs distance.

on the nucleus itself should be possible on a fairly large sample of nuclei.
Observing modes:
Imaging is a basic tool, but spectroscopy is mandatory (typical resolution $\approx 3000 = 100$ km/s).

Because a large fraction of the light from an AGN is in fact reflected, a strong polarization is often measured and a polarimetric capability of an AO system is certainly desirable. This is also true for a coronographic mode that should be extremely useful when tackling the question of the direct environment of an AGN.

WF sensing on faint objects:

- AGN : most of these objects are faint (less than 200 have V≤14, 1000 have V≤ 16 and 2800 have V≤ 18; Veron-Cety Catalog).

  Note that the number of confirmed AGNs will increase dramatically during the next few years as a consequence of large scale surveys about to start at CFHT and AAT and they will be fainter than V=16.

- ULIRGs have magnitudes in the range $R = 13.5$–18 (in the first 5 arcsec).

- starbursts: the number of objects with $m_{\rm V} < 14$ and 16 is about 200 and 700 respectively. This means that one can expect more than 100 objects to be observable with a Strehl ratio larger than 0.4. The strong evolution of the number of objects with redshift implies that it will be possible to discuss the evolution of the starburst properties and their relation to AGNs.

IR WF sensing:
ULIRG : magnitudes of ULIRG are typically $K = 8.9$–13.6 and $N \sim 6$ (central regions, 5"). In the sample of Carico et al. (1990), 58 out of 65 (89%) have $K < 12.5$. In the absence of LGS, an IRWFS is well suited for these objects.

WF sensing on extended objects:
AGN, starburst galaxies and ultra luminous IR galaxies (ULIRG) are extended.

- AGN: it is possible to use only their unresolved core. These objects will be wavefront sensed with the visible WFS.

- starbursts: experience with other AO systems is that on starburst galaxies, a field of 1.5" on the WFS enables to close the loop on only 50% of objects selected to have a priori a bright enough nucleus. This lead us to recommend 3". These objects will be wavefront sensed with the visible WFS.

- ULIRG typical extend is of the order of 30 arcsec (Sanders et al. 1988). They will most probably be sensed with the IR WFS. The $FWHM$ of the central region is smaller than 2 arcsec in the K-band for most of the cases.

An important parameter is the luminosity profile of these extended objects. Most generally, the bulb (deVaucouleur's Law) dominates the disk distribution close to the nucleus (Kotilainen et al, 1993). Observations prior to the AO ones may be needed to investigate these luminosity profiles.

Mosaicing:
Mosaicing may be needed (e.g. starbursts, up to 40")

2.10 QSOs hosts:

2.10.1 Astrophysical issues:

An important challenge is to observe the hosts of QSOs. HST images show that intrinsically luminous quasars occur in diverse environments that include ellipticals as bright as the brightest cluster galaxies (10%), apparently normal ellipticals (50%), apparently normal spirals (15%), interacting systems (15%) and faint surrounding nebulosities (10%) (Bahcall et al. 1997). There are more radio quiet quasars in galaxies that appear to be ellipticals than in spiral hosts contrary to expectations. However at least half of the radio loud quasars have detectable elliptical hosts. To observe the QSO hosts as close as possible to the QSOs, one needs the best contrast, and hence correction, as the average absolute magnitude of the hosts is 2.2 magnitudes brighter than expected for a galaxy luminosity function. At a typical redshift of 0.2, the host-galaxy has a R-luminosity about 2 to 3 magnitudes less than the quasar and has an extension of about 5 arcsec down to R = 25 mag arcsec^{-2}. This means that one can expect K $\sim$ 21.5 and H $\sim$ 22 mag arcsec^{-2}. These performances can be achieved if a Strehl ratio of at least 0.5 is obtained on the quasar itself.

Most of the quasars with V magnitude smaller than 16 could be used for correction. This makes the quasars at $z < 0.3$ ideal for investigating the difference between radio-loud and radio-quiet quasars.

2.10.2 Implications for the AO system:

Need for WF sensing on faint objects:
There are only 116 QSO brighter than V=16 compared to 1334 brighter than V=18 in the Hewitt and Burbidge Catalog. In particular, high redshift QSOs are fainter than V=16. Note that the V-K of these objects is not large enough to use instead an IR WFS. These targets will be used to study the host galaxies at $z < 1$ and the emission counterpart of QSO absorption lines up to the highest redshifts. Full correction is not required for these programs. Note that the number of confirmed QSOs will increase dramatically during the next few years as a consequence of large scale surveys about to start at CFHT and AAT and they will be fainter than V=16.

2.11 Extragalactic distance scale:

2.11.1 Astrophysical issues:

HST observations have shown the possibility of improving our estimations of distances of nearby galaxies (e.g. M100; Ferrarese et al, 1996) by observing the cepheid population. Other distance indicators such as RR Lyrae, planetary nebulae or SN may be used even for more remote galaxies. This in turn enables a more accurate estimation of the Hubble constant. To do so, the best angular resolution is needed and AO on large telescopes will do better than HST: more remote galaxies will be sensed and close galaxies studied in greater details.

2.11.2 Implications for the AO system:

Depending on the cases, LGS will be needed.

2.12 Deep sensus of empty fields:

2.12.1 Astrophysical issues:

Deep sensus of empty fields (e.g. Hubble Deep Field) are needed to study the morphological properties of remote galaxies, so as to understand the evolution of galaxies since the earliest ages of the Universe.

2.12.2 Implications for the AO system:

In that case, either a natural guide star or the LGS can be used. For LGS, a reference source for tilt is nevertheless needed. The respective resulting image qualities will depend on off axis degradation and diffused light in the case of natural guide star.

2.13 Conclusions:

AO on large telescopes will enable deeper insights in all domains of astrophysics, and also openings to new studies. We summarize here the implications for the AO instruments:

- high ($\geq$ 50 %) SRs are needed for bright objects (V=13–14 for the visible WFS),
- faint objects (up to V=18) should be used for wavefront sensing, so as to achieve a number of astrophysically very important programs on faint sources (e.g. extragalactic sources), and also to increase the sky coverage,
- an IR WFS is mandatory to use very red objects as reference sources,
- extended objects (up to $\simeq$ 3" in size) should be usable as reference sources,
- objects with non negligible proper motions should be usable as references sources,
- a wide variety of observing modes: imaging (broad band and narrow band), mosaicing, spectroscopy, coronography, polarimetry,
- finally, when observing at thermal wavelengths, chopping capabilities are needed, as well as counter chopping facilities to improve the overall efficiency.

3 NAOS and CONICA:

NAOS (Rousset et al., 1998) is the adaptive optics system for UT1/VLT. It will be attached to the adaptor rotator and will feed the science instrument CONICA. CONICA will be rigidly attached to NAOS. Both will rotate at the Nasmyth focus. A view of the system is provided in Fig. 2.

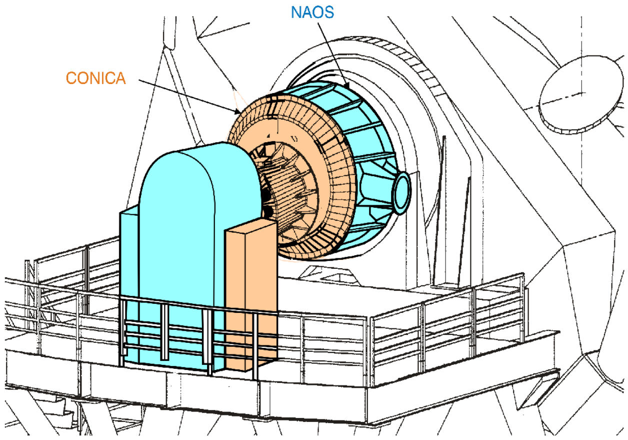


Figure 2: Global view of the NAOS+CONICA systems attached to the Nasmyth focus.

3.1 NAOS:

3.1.1 System:

Like any AO system, NAOS basically consists of 2 main parts:

1) a wavefront sensor (WFS): in the case of NAOS, a Shack Hartman type technique has been adopted. Two different WFSs will be used: a WFS working in the visible (0.45–1 μm ; VWFS) and an IR one (IR WFS). The detector will be read at a rate up to 500 Hz, adjustable by steps of 10 Hz. The visible camera will be a 128$\times$128 EG&G CCD developed at ESO headquarters. Its quantum efficiency is $\simeq$ 80% and its read out noise about 4e- at 500 Hz.
   The IR WFS detector will be 1024$\times$1024 Rockwell Hawaii array (only a small part of it, 100$\times$100 pixels, will be used), read at a maximum rate of 200 Hz (step=10 Hz).

   The visible WFS will use different lenslets arrays: 14$\times$14 subpupils (144 valid) and 7$\times$ 7 subpupils (36 valid), allowing different subpupil sizes, in order to optimize the correction under various atmospheric conditions and various reference objects (bright/faint, extended or not).

2) the corrective optics: a tip-tilt mirror will compensate for the tilt fluctuations (5" peak-to-peak stroke) and a deformable mirror will compensate for higher orders of atmospheric turbulence. The deformable mirror shape will be controled by an array of 185 active actuators (10 μm peak-to-peak stroke).

NAOS is intended to use either astronomical objects or a laser guide star as reference objects. In the latter case however, a natural guide star (NGS) will be necessary to correct for tip-tilt correction.

3.1.2 Optical properties:

The optical lay-out of NAOS is shown in Fig. 3. The beam from the telescope enters at f/15 and will feed CONICA at f/15 as well. The incoming beam is separated between the science instrument and NAOS by a dichroic. A set of different dichroics will be provided to optimize the respective fluxes in the NAOS and CONICA channels, according to the science requirements.

A field selector, located at the entrance of the WFS channel will provide an unvignetted field of view (FOV) of 2 arcmins in diameter, allowing then to use reference objects within 2 arcmins from the science targets. It will also allow to select in this FOV a NGS for tip-tilt correction in cases where the LGS is used. When working in thermal domains, the field selector should also allow to perform chopping and counter-chopping.

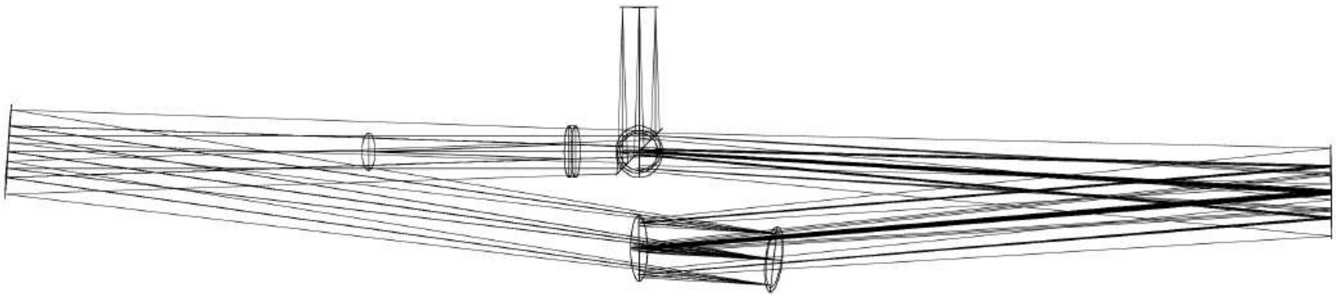


Figure 3: Optical lay-out of the NAOS system.

3.2 CONICA:

CONICA is a spectro-imager working between 1 and 5 μm (Lenzen et al., 1998). Different cameras will be available to ensure proper sampling of the images in this wavelength range. CONICA FOVs will range between 14" and 70". CONICA will provide several observing modes:

- broad band imaging,
- narrow band imaging, with various sets of filters centered at the most astronomically interesting wavelengths,
- spectroscopy at resolutions ranging between 50 and 500 as well as a Fabry Perot mode (K band), providing a resolution of 1800,
- polarimetry (wiregrids and Wollaston prism)
- coronography with various sets of masks adapted to the J, H, and K wavelengths.

CONICA's detector will be an SBRC, which covers the whole 1-5 μm domain. It has a well capacity of 200000 e- and a read-out-noise of about 25 e-.

3.3 Organisation:

NAOS is currently being designed in France, within an ONERA/INSU (DESPA, Meudon; LAOG Grenoble) consortium. CONICA is being built in Heidelberg (Germany). Both NAOS and CONICA are expected to be tested on the sky at the end of year 2000.

3.4 Comparison with other AO systems:

Compared to AO systems on 4-m class telescopes, NAOS on the VLT will provide not only a better angular resolution (factor of 2) but also an improved image quality, with SR $\simeq$ 80% on bright objects, to be compared to SR of typ. 30-50 % presently obtained. Also, it will allow to use fainter reference objects, typ. V = 17-18 to be compared to V = 13-14 at present time.

Compared to other systems currently built for other large telescopes (e.g. KECK, GEMINI, SUBARU), NAOS will have similar or better performances in terms of SR. The functionalities vary from one system to the other.

4 Expected performances and capabilities:

4.1 Wavefront sensing performances and capabilities:

The expected performances in terms of SR are reported in Fig. 4 for the visible WFS. It can be seen that:

- high SR will be obtained on bright objects (V=13–14),
- objects as faint as V=18 can be used as references sources, with a significant angular resolution improvement. This is particularly interesting for the extragalactical studies,
- for a given reference object, the achievable SR strongly depends on seeing conditions: a 10% increase in SR is expected with a seeing of 0.65" instead of 0.85" for bright objects (V $\leq$ 13), and a factor of 2 increase is expected for objects fainter than V=15.5. The atmospheric conditions must then be a major criterion for the sheduling of the observations.

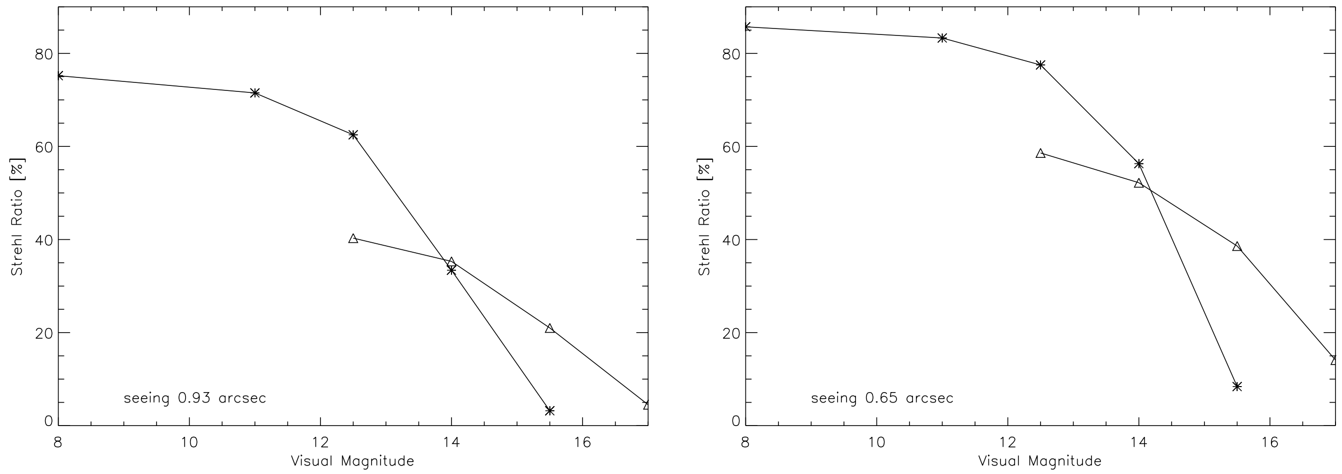


Figure 4: Sr vs V magnitude for 0.93" (left) and 0.65 "(right) seeings stars represent values obtained with the 14×14 subapertures and triangles values obtained with the 7×7 subapertures.

Fig. 5 gives examples of simulated Point Spread Functions (PSF) with SR of 70% and 56%. Twice as much energy is left in the region $\simeq$ 0.25–0.5" from the center in the 56% SR PSF compared to the 70% SR PSF (K band). No significant difference is seen further away. The difference will then affect observations of objects separated by less than 0.25–0.5". If this halo can be properly subtracted, the loss will come from the photon noise of this halo, and is then about a factor $\sqrt{2}$, i.e. less than 0.5 magnitude. If on the contrary, and may be more realistically, the halo is not well subtracted, the loss will be a factor of 2, i.e. $\simeq$ 1 magnitude. Of course, increasing the exposure time would not compensate for this loss. Examples of the impact of SR improvement are given in Fig. 6 and 7 in case of 1) a binary system with a separation of 0.3" and ΔK of 6.0, observed with NAOS and CONICA with bother SRs, and 2) a typical globular cluster.

In terms of angular resolution, the simulations show that for bright objects, the PSFs are diffraction limited down to the optical domain for seeings $\leq$ 0.85", eventhough of course, the SR gets much lower (Fig. 8 and 9). Observations in the optical domain will therefore also benefit from the use of AO. This justifies the choice to implement in NAOS an extra output to feed a second instrument working in the visible domain.

It is important to stress on the importance of the Q sheduling which will allow to get the best SR on both bright and faint reference sources. Also, Q sheduling will be important for scientific programmes requiring large FOVs. This underlines the importance of atmospheric conditions monitoring and predictions.

The performances expected with the IR WFS are summarized in Fig. 10. The comparison between both WFS performances shows that the IR WFS is competitive with the visible WFS as soon as the objects have a V-K $\geq$ 2–3, hence for all stars cooler than K0 type (Allen, 1991). The two WFSs will provide roughly similar sky coverages. The real advantage of the IR WFS is that it will allow to use very red objects as references, which has

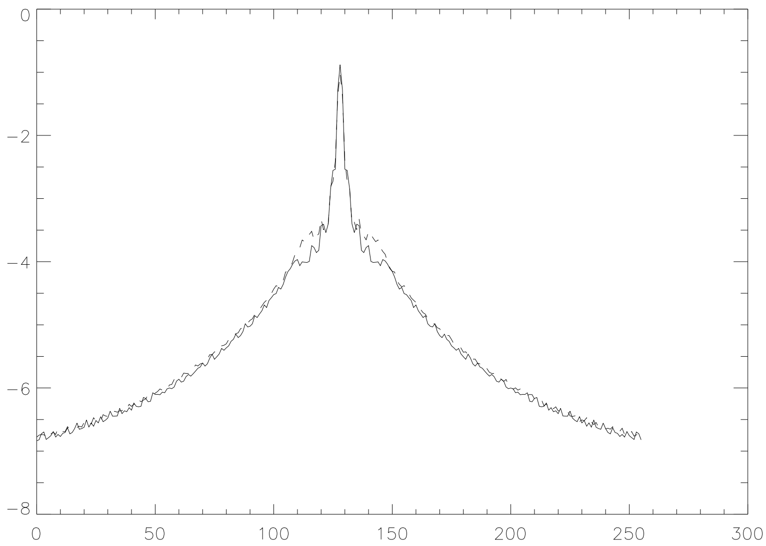
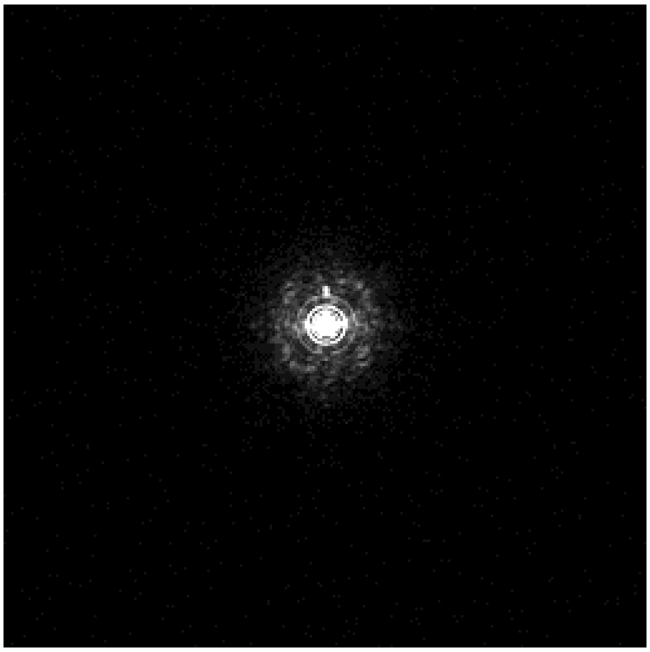


Figure 5: Superimposition of two PSFs at K, one with Sr=0.71 (solid) and one with Sr=0.56 (dashed). On the x-axis, pixel scale $\simeq$ 0.024". Log. scale.



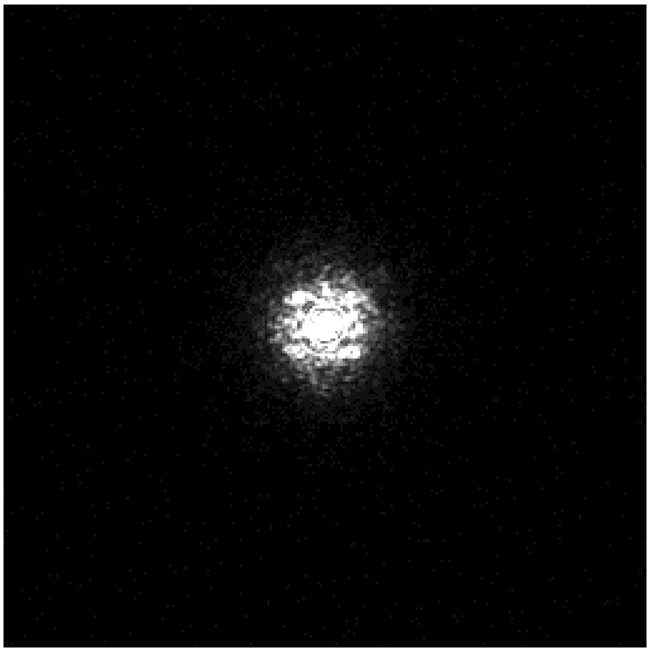


Figure 6: Simulation of images of a binary system with a separation of 0.35" and a ΔK of 6.0 with NAOS+CONICA and Sr=0.71 (left) and Sr=0.56 (right). Same cuts are used in both figures.

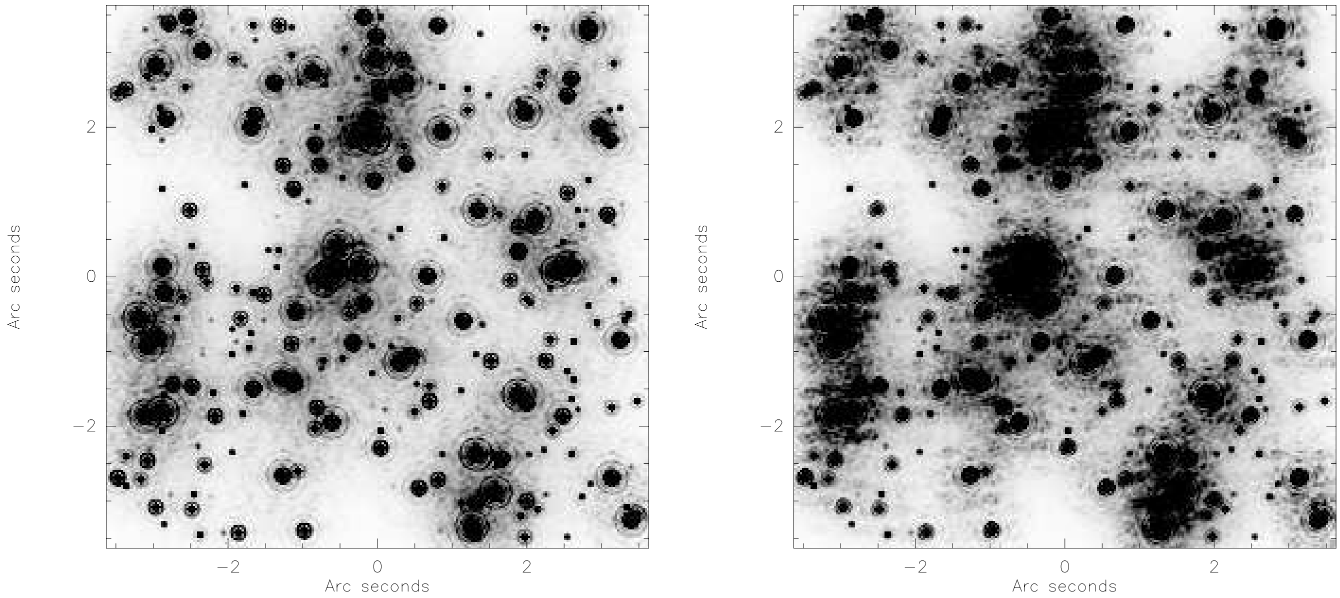


Figure 7: Simulation of a typical globular cluster observed with NAOS+CONICA and Sr=0.71 (left) and Sr=0.56 (right). Same cuts are used in both figures.

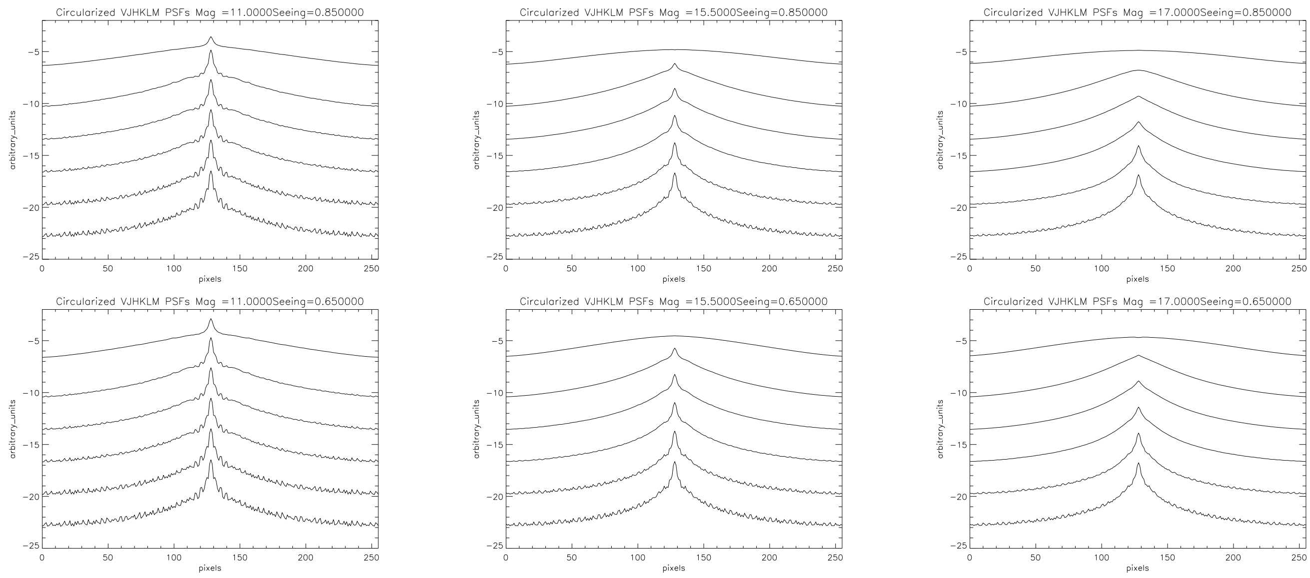


Figure 8: On axis simulated V, J, H, K, L, M PSFs for references objects with V magnitudes of 11.0 (left) ,15.5 (middle) ,17.0' (right) under two seeings : 0.85" (top) and 0.65" (bottom).

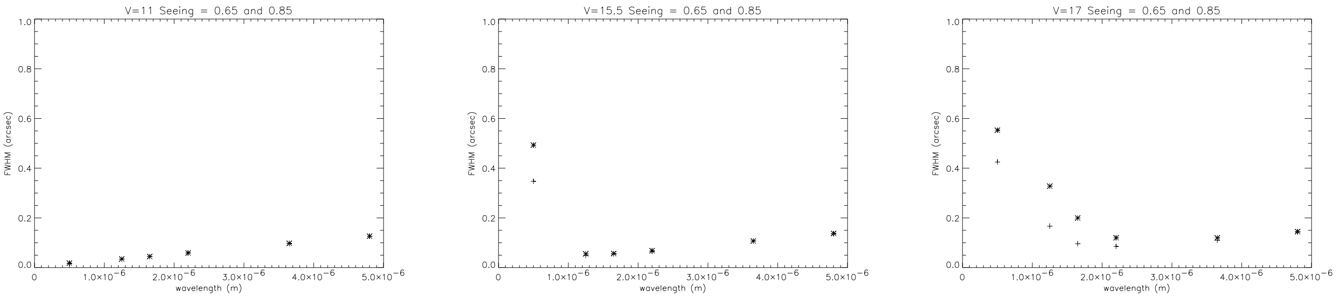


Figure 9: On axis V, J, H, K, L, and M FHWM (arcsecs) for reference objects with V magnitudes of 11.0 (left) ,15.5 (middle),17.0 (right) and seeings of 0.65” and 0.85”

impact on the study of late type stars, very young and embedded objects, objects in very obscured regions such as the galactic center, and infrared galaxies.

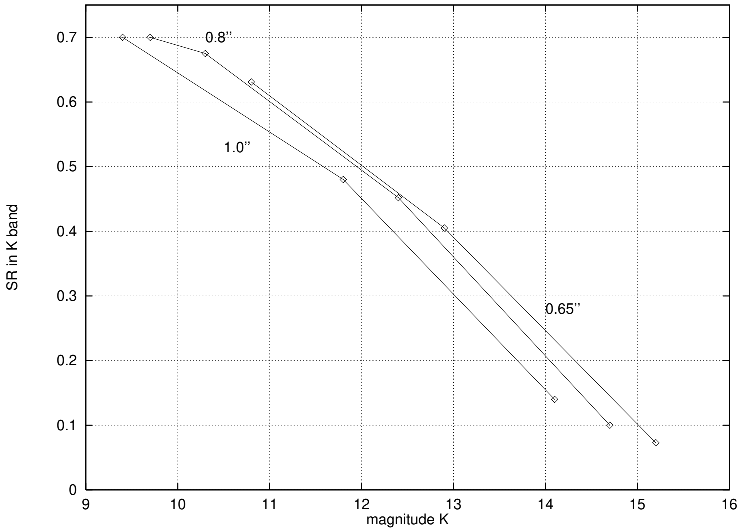


Figure 10: Performance with the IR WFS at 1.00 (dashed line) and 0.85arcsec (solid line) seeing

Finally, both WFSs will offer the opportunity to use extended objects as reference sources, with sizes up to $\simeq$ 3.5”, which has impact on solar system planets studies (e.g. when using satellites as references) but also on extragalactical studies (when using the cores of the galaxies as references).

4.2 Optomechanical capabilities:

The optomechanical capabilities currently include chopping and counter-chopping facilities, at rates $\leq$ 0.25 Hz. This is important for observations longward of K. The field selector will moreover ensure a proper repositioning after chopping, or precise differential positioning. The field selector will finally provide tracking capabilities of $\simeq$ 5.5 mas/s, allowing the use of high proper motion objects as reference sources (e.g. satellites of big planets). The stability constraints on the whole system will ensure a stability of about $\lambda/8\,\mathrm{D}$ over about 20 minutes on the CONICA detector.

Finally the current optomechanical design includes the provision for an extra output channel, to feed any instrument weighting less than $\simeq$ 60 kg, and complying with the optomechanical interface. Visible cameras, or entrance fibers will then be adaptable.

4.3 Overall NAOS+CONICA sensitivity:

The expected sensitivity of CONICA+NAOS are given in Fig. 11. The use of AO greatly improves the overall sensitivity since high SR means a high core intensity for point like sources. It moreover improves the detectivity of faint sources close to bright objects, as already seen.

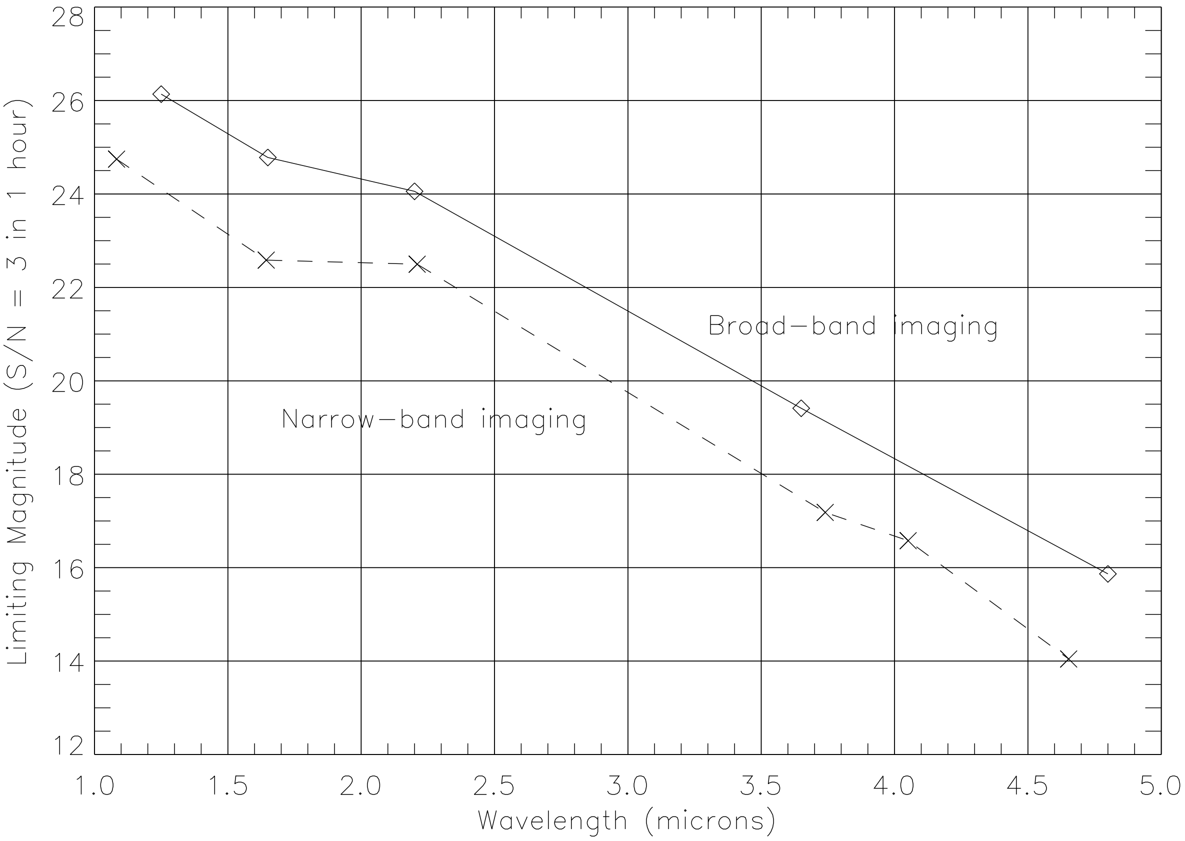


Figure 11: NAOS+CONICA limiting magnitudes for a diffraction-limited source

4.4 Software capabilities:

An important issue for the astronomer is software. The preparation of the observations will be a crucial phasis. To get the best results, the astronomer will need to know, for each astronomical target and for each wavelength of observation, the best reference source, the best NAOS configuration (which WFS? which associated parameters? which dichroic?). Of course, the answer will depend on the atmopsheric conditions. This requires a dedicated and powerful performance simulator. At the same time, this simulator must be simple enough so that non AO specialists may use it. Also, helps will be given to perform the simulations.

The performance simulator should also be used in case of Q sheduling, to optimize the efficiency of the AO observations.

During the observations, various informations will be given to the astronomer: PSF estimated from the WFS data; evolution of atmospheric conditions etc..

Finally, NAOS will provide the user with pre-reduced WFS data, to be used for post processing of the astronomical data (Véran et al., 1997; Rigaut et al., 1998b).

5 Conclusions

NAOS will then provide the opportunity to get the best possible images from the ground: highest SR, stable images, ability to use faint objects as references, and later on the possibility to use an LGS. To optimize the observations, a special care will be taken from the system to provide the astronomer with dedicated simulation tools. Of course, the global performances will also depend on the overall VLT flexibility, and in particular the ability to optimize the observations according to changing atmospheric conditions. This ability will certainly improve with the on-site experience.

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