SINFONI: A near infrared AO assisted integral field spectrometer for the VLT

N. Thatte,[a] M. Tecza,[a] F. Eisenhauer,[a] S. Mengel,[a] A. Krabbe,[c] S. Pak,[a] R. Genzel[a] and D.Bonaccini,[b] E. Emsellem,[d] F. Rigaut,[b] B. Delabre,[b] G. Monnet[b]

[a]Max-Planck-Institut für extraterrestrische Physik, Postbox 1603, D–85748 Garching, Germany.

[b]European Southern Observatory, Karl-Schwarzschild straße 2, D–85748 Garching, Germany.

[c]DLR, Institut für Weltraum Sensorik, Rudower Chausse 5, D–12489 Berlin-Adlershof, Germany.

[d]Observatoire de Lyon, 9, Av. Charles-Andre, F–69561 Saint-Genis Laval Cedex, France.

ABSTRACT

SINFONI, the SINgle Faint Object Near-infrared Investigation, is an instrument for the Very Large Telescope (VLT), designed to provide *spectroscopy at the telescope diffraction limit* in the near-infrared. This unique capability is achieved by combining two state-of-the-art developments, an integral field spectrometer (SPIFFI) and a curvature sensor based adaptive optics system (MACAO). SINFONI is a collaborative effort by the Max-Planck-Institut für extraterrestrische Physik (MPE) and the European Southern Observatory (ESO).

SINFONI will operate at the Cassegrain focus of Unit Telescope 1 (UT1) of the VLT, in conjunction with a Laser Guide Star (LGS) for almost complete sky coverage. It will provide integral field data cubes, with a hexagonal field of view ranging from $\sim 1''$ to $8''$, with corresponding pixel sizes of $0\farcs03$ to $0\farcs25$. The field of view contains 1024 spatial pixels, with ~100% filling factor in the focal plane. Spectra are obtained for each of the 1024 pixels. Spectral resolutions of R=2000 to R=4500 will be available, covering the J, H and K spectral windows. The high spectral resolution mode will allow software OH suppression in the J and H bands. The detector is a 1024^2 HgCdTe HAWAII array from Rockwell. Spectroscopy of faint objects ($m_K < 21$ and $m_H < 22$) will be easily feasible.

Keywords: spectroscopy, diffraction limit, near infrared, integral field, adaptive optics

1. INTRODUCTION

The promise of achieving resolution close to the diffraction limit of the telescope has been largely fulfilled by adaptive optics systems in recent years. The addition of laser guide stars has extended the coverage of adaptive optics systems to almost the whole sky, in contrast to the past, when adaptive optics was limited to the vicinity of bright reference sources. However, few efforts are underway to do spectroscopy at high spatial resolution, close to the telescope diffraction limit. Recently, the ADONIS system at the European Southern Observatory (ESO) has been equipped with Fabry-Perot spectroscopic capabilities (SHARP 2)[1],[2] the MPE 3D spectrometer[3] is being attached to the ALFA system,[4] and OASIS, the successor to TIGER[5] at the Canada-France-Hawaii Telescope (CFHT) has been taking AO assisted spectra at visible wavelengths.

Integral field spectroscopy is ideally suited for use with adaptive optics. The PSF variability of AO systems can be coped for, via deconvolution of the images and by the fact that the full spectrum is obtained at the same time as the image. This is not the case with Fabry-Perot spectrometers or with broadened slit spectro-interferometers.

The Very Large Telescope project's (VLT) 8 meter telescopes provide diffraction limited resolution of ~50 mas in the near-infrared, rivaling even the capabilities of current space telescopes. The desire to exploit this high resolution for spectroscopy led to the concept of SINFONI, the SINgle Faint Object Near-infrared Investigation, a collaborative effort between the Max-Planck-Institut für extraterrestrische Physik (MPE) and the European Southern Observatory (ESO). SINFONI brings together two separate developments, a near-infrared integral field spectrometer SPIFFI,[6] and a curvature sensor based adaptive optics system MACAO.

(Send correspondence to N.Thatte)
N.Thatte: E-mail: thatte@mpe.mpg.de
D.Bonaccini: E-mail: dbonacci@eso.org

Detailed explanations of the SINFONI concept are divided as follows: We first elaborate on general concepts for doing spectroscopy at the diffraction limit. Next, we describe the spectrometer SPIFFI, followed by the adaptive optics system MACAO and the interface between the two. Finally, the SINFONI section presents the instrument sensitivities expected.

2. DIFFRACTION LIMITED SPECTROSCOPY

2.1. Spectroscopy close to the telescope diffraction limit

Most spectrometers, either long slit or integral field, have slit sizes much larger than the diffraction limit of the telescope. In these instruments, slit diffraction is not important. However, instruments operating in conjunction with adaptive optics systems need to deconvolve the PSF in order to recover the full spatial resolution of the telescope. An integral field spectrometer, operating with an AO system, needs a pixel size (effective slit width) smaller than half the diffraction limited resolution of the telescope, in order to Nyquist sample the PSF. Slit diffraction becomes important at these slit widths, and there are a few special points to consider before designing such a spectrometer:

- In the presence of strong slit diffraction, the pupil image at the dispersion grating is blurred. Thus, a pupil stop placed at the grating is ineffective in blocking off thermal background from the telescope structure and other warm parts of the instrument. An extra cryogenic pupil stop must be placed in the light path before the light enters the slit (i.e. in the pre-optics).
- The beam entering the spectrometer is much wider (has a numerically smaller focal ratio) than that predicted by geometrical optics, due to strong diffraction at the slit. As a result, the spectrometer must be designed to pass an A–Ω product greater than the geometrically computed throughput. Figure 1 plots the over design factor for a spectrometer for an 8 meter telescope as a function of the slit width. For a K band spectrometer with Nyquist sampled pixels (slits), the over design factor is a little over 3. This calculation was done in 1–D only, but a similar result holds for the two dimensional case.
- The number of grooves covered by the pupil image at the grating must be computed taking into account the effects of slit diffraction. The spectral resolution of the spectrograph is influenced by the number of grating grooves, and needs to be correctly computed.

2.2. Spectroscopy with adaptive optics

Spectroscopy with an adaptive optics system is complicated by the fact that only part of the energy is concentrated within the diffraction limited Point Spread Function (PSF) of the telescope. The rest is distributed in a seeing-limited halo. Hence, deconvolution or post-processing of images is normally done to recover the full spatial resolution. For slit spectrometers, this is not possible without a separate imaging mode, because the two dimensional PSF is not available to a slit spectrometer.

Fabry-Perot spectrometers and broad-slit spectro-interferometers are more successful, since they can access the two-dimensional PSF very well. However, they painfully suffer from inhomogeneities in the data cube, due to time variations in the PSF delivered by the adaptive optics system, and also to time variations in atmospheric transmission, especially in the near-infrared. For these reasons, an integral field spectrometer, one which can obtain an entire data cube (two spatial and one spectral dimension) in one exposure, is ideally suited to do spectroscopy with an adaptive optics system.

The advantage of using AO for spectroscopy lies in the increase of photon concentration, as well as in the diffraction limited performance. Plots of encircled energy and Strehl ratios quantifying our case are presented in section 4. Adaptive optics performance improves as the wavelength increases, since there are fewer cells of atmosphere above the telescope aperture. On the other hand, the sensitivity of spectrometers decreases at wavelengths long-ward of 2.2 μm, due to excess noise resulting from thermal background from the telescope and atmosphere. Hence, the near infrared H and K windows are best suited for high resolution ground based spectroscopy.

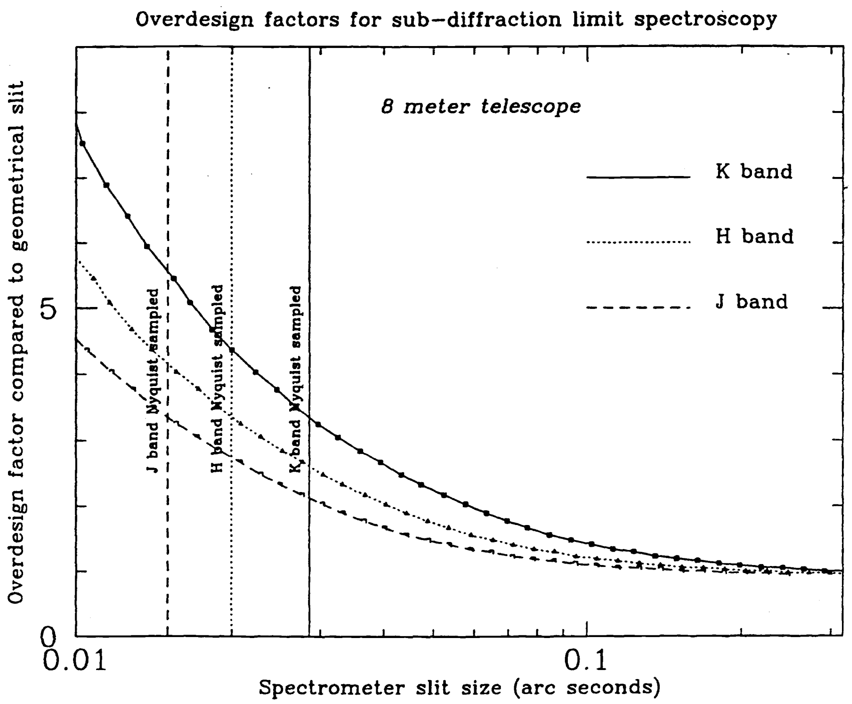

Figure 1. Plot showing the over design factor required for a spectrometer to take into account the effects of slit diffraction. The curves show the factor by which the pupil stop must be oversized to include 90% of the energy from the telescope. Results refer to a one dimensional calculation.

3. SPIFFI

SPIFFI - the SPectrometer for Infrared Fiber-fed Field Imaging, is an ongoing development at MPE for the last three years. It is a near-infrared integral field spectrometer which provides spectra of 1024 pixels fully filling a hexagonal field of view in a single exposure. The pixel scales on the sky can be chosen (via flip-in optics in the pre-optics) within the range 0."03 to 0."25 per pixel. The corresponding field of view ranges from ~1" to 8". Spectral resolutions ranging from R=2000 to R=4500 are available. The observer may choose one of four gratings located on a grating wheel. Simultaneous wavelength coverage at high spectral resolution is restricted to one of the J, H or K atmospheric windows, while at low resolution, simultaneous coverage of the H and K bands is possible. SPIFFI is a fully cryogenic instrument, with the pre-optics, image slicer, and spectrometer sections all cooled to 77 K using liquid nitrogen.

3.1. The Image Slicer

The heart of SPIFFI is a cryogenic image slicer, which rearranges the light from a two dimensional filled focal plane into a long slit which is fed to the spectrometer section. Various concepts for image slicers can be found in the literature, but very few are suited to low temperature operation. The MPE 3D imaging spectrometer has successfully used a twin set of flat mirrors to make a near infrared image slicer. Although this concept is easily adapted to low temperature operation, the corresponding slit size (> 30 cm) leads to large spectrometer optics.

Instead, the novel SPIFFI image slicer concept uses flared optical fibers to do the image slicing.[6] Several image slicers use optical fibers fed by an array of lenslets in order to re-arrange the light in the focal plane, with close to 100% filling factor. Conventional designs use transmissive glues to couple the light from the lenslet into the fibers, or involve complex positioning systems to align the fiber axes with those of the individual lenslets. Neither of these technologies is amenable to cryogenic use.

The SPIFFI concept fabricates the lenslet and the fiber as a monolithic unit, thus preventing differential thermal contraction from affecting the lenslet-fiber alignment. OH free silica-silica fibers are flared in a process akin to the reverse of drawing the fiber. After flaring the fiber by a factor of 15, a spherical lenslet with hexagonal cross section is polished onto the flared tip. These monolithic fiber-lenslet sub-units are then arranged in a close packed hexagonal geometry to form the image slicer. At the other end, the fibers are arranged in a zig-zag geometry to form a 3 tier long slit.

3.2. The Spectrometer

Figure 2 shows the layout of the SPIFFI spectrometer optics. The spectrometer itself consists of a refractive collimator, 4 gratings on a grating wheel oriented in the Ebert configuration, and a folded Schmidt camera. An additional distortion correcting and field flattening doublet is placed close to the detector, in order to get the spectra aligned precisely with the columns of the detector, with very little spillover ($< 5\%$ over the entire detector). The detector itself is a 1024^2 format HAWAII array (HgCdTe) from Rockwell, sensitive upto 2.5 μm.

Perspective view of SINFONI spectrometer optics

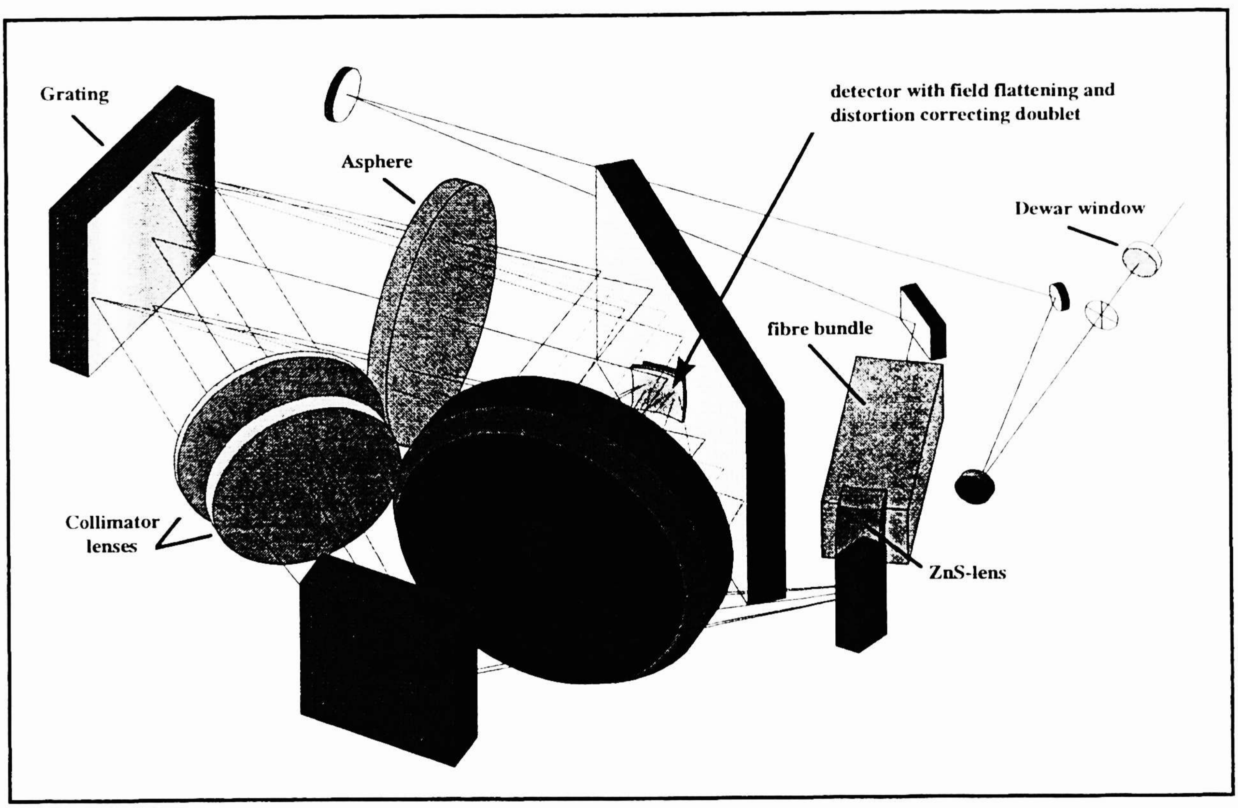

Figure 2. Perspective view of the SPIFFI spectrometer optics. The fiber slicer is shown schematically as a box which rearranges the hexagonal input field to a long slit. The dewar entrance window also serves as a beam splitter.

4. MACAO

The Multiple Application Curvature Adaptive Optics planned for SINFONI is tailored to the SPIFFI integral field spectrograph. MACAO has to work with faint Natural (NGS) and Laser (LGS) Guide Stars, as the main targets are extragalactic objects. MACAO is the first curvature system we know of, being designed for operation with LGS. The use of faint NGS or LGS, will reduce the performance of the system due to the lack of photons or the cone effect, respectively. Hence the number of actuators for MACAO has been tuned to provide diffraction limited resolution in J–H–K bands, with 0.45 Strehl values in K-band under median Paranal seeing conditions. Fewer, larger sub-apertures allow larger photon collection. The foreseen use of EG&G Slik Avalanche Photo-Diodes (APD) optimizes performance in the faint NGS regime.

The encircled energy within 0.″1 radius is the mean performance parameter sought for, as it is important for faint object, extragalactic spectroscopy. MACAO is based on a curvature system design, with 35 actuators and sensor elements, arranged in a circular geometry as shown in fig. 3. At bright flux levels, this should allow correction of the first 26–28 Karhunen Loewe (K–L) modes. The choice of a curvature system is optimal in this case, as the number of K–L modes to correct is moderate, and curvature systems give optimal efficiency (80%) in the ratio [corrected K–L modes]/[number of actuators]. The use of APDs for the wavefront sensor is also optimized for faint NGS, and gives fast loop response times cutting down the servo-loop time delay error. This is particularly important at Paranal, where fast seeing is often measured.

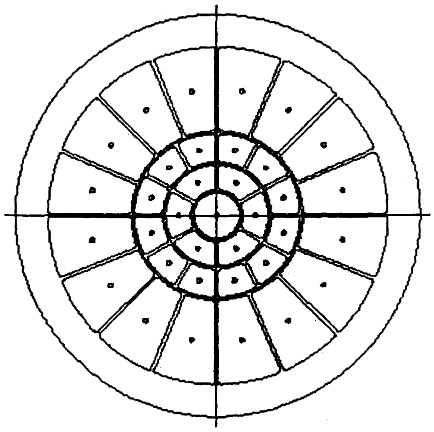

Figure 3. Layout of the 35 element wavefront sensor, with the APDs centered on each lenslet element

A separate tip-tilt system, STRAP,[7] has been developed and built at ESO for the AO systems working with LGS. STRAP is optimized to correct tip-tilt errors using a NGS, and it is fully integrated into MACAO. A custom development of the curvature sensor, based on EG&G's Slik APD is done for MACAO. This builds on the STRAP quad-cell development, making a distributed and integrated array of diodes, directly coupled with the input lenslet, with the quenching, the photon counting electronics and curvature signal extraction already on board with the sensor. This development ensures customized electronics functionality for AO use, an optimal throughput, a rugged WFS, and a general improvement in maintenance and servicing of the sub-unit.

MACAO is the first of a series of curvature AO systems being cloned for the VLT from a breadboard master, as presented at this same conference.

4.1. MACAO optical layout

The optomechanics of MACAO is embedded in SINFONI, and it is designed to integrate as much as possible its functions and operations with SPIFFI. The optical relay (Figure 4) transfers the input f/13.4 VLT-Cass image to SPIFFI's cold f/17 focal plane, located 10cm inside the entrance window of the dewar. The design is entirely reflective with two off-axis parabolas as optically active elements, and the number of mirrors is minimized to four. Enhanced silver coatings are selected such as Denton Vacuum's FS-99, which give excellent reflectivity from the visible to the NIR, very low emissivity, and are chemically removable for re-coating.

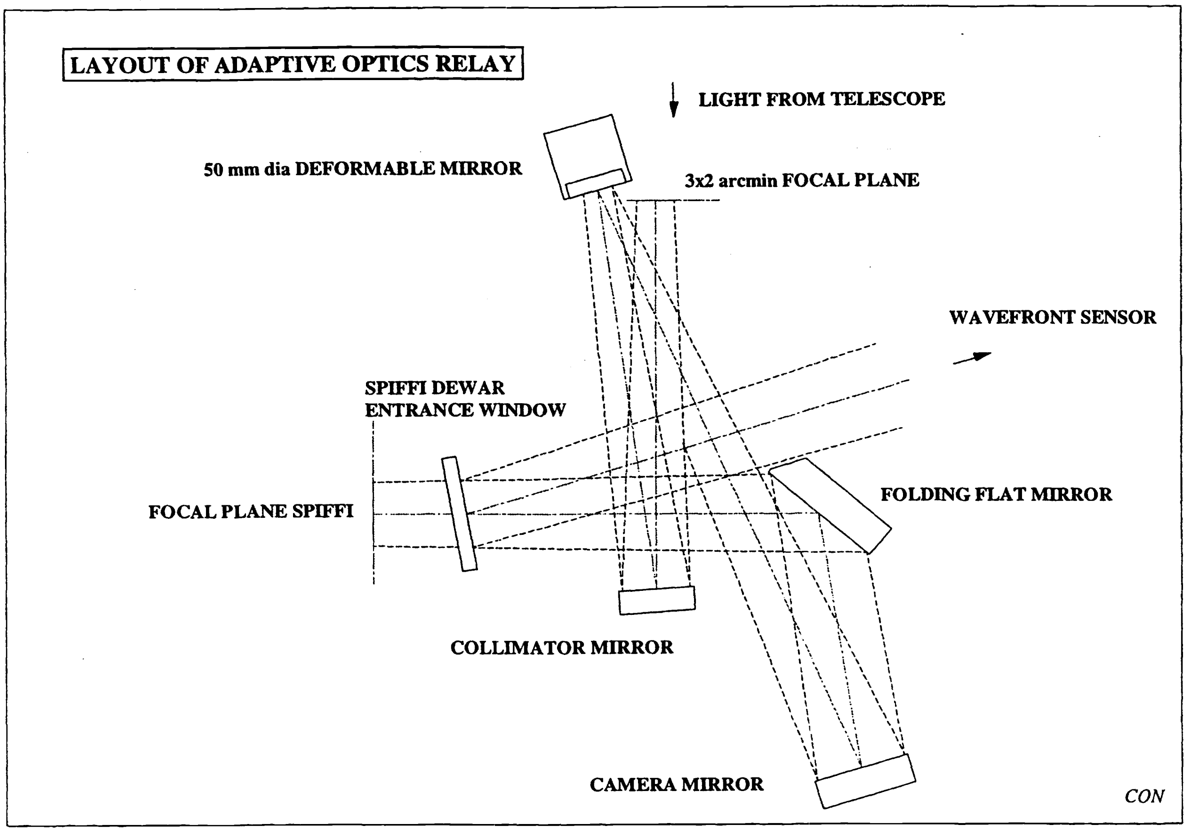

Figure 4. Optical layout of the MACAO relay optics, from the VLT Cass focus to the SPIFFI cold focal plane. The SPIFFI dewar window acts as a dichroic to send the visible light to the WFS. 2 × 3 arcmin of field are transferred, to allow for NGS selection

There is no specific tip-tilt mirror in the optical relay. The high temporal frequency, low stroke tilt signal is sent to the curvature bimorph mirror. The low frequency, high stroke tilt signal is sent by MACAO to the VLT secondary mirror.

The dichroic which sends the visible light to the wavefront sensor is SPIFFI's entrance window, there are thus no warm dichroics which may inject thermal radiation into SPIFFI, reflected from the side. This is a difference with common AO designs, where the dichroics are inserted in the beam with no measures taken to minimize thermal radiation injection into the IR instrument.

4.2. MACAO optomechanics

The optomechanical layout of MACAO is shown in Fig. 5. Motorization controls and calibration units are shared by the two instruments. The optomechanical design of MACAO is modular, and its design drivers are:

- MACAO opto-mechanical components may be accessed without removing SPIFFI, both instruments are mounted in the SINFONI mechanical interface (Fig. 6)
- The entire AO system, MACAO, may be slid off of SINFONI for servicing, without dismounting other systems.
- The AO system is mounted in a light-tight cover, and it may be operated with artificial sources and turbulence generators during daytime. This feature will allow us to train operators, and refine and check the system without using precious telescope night-time.

• The positioning of SPIFFI's entrance window is precisely constrained by the MACAO optomechanics and its interface flange.

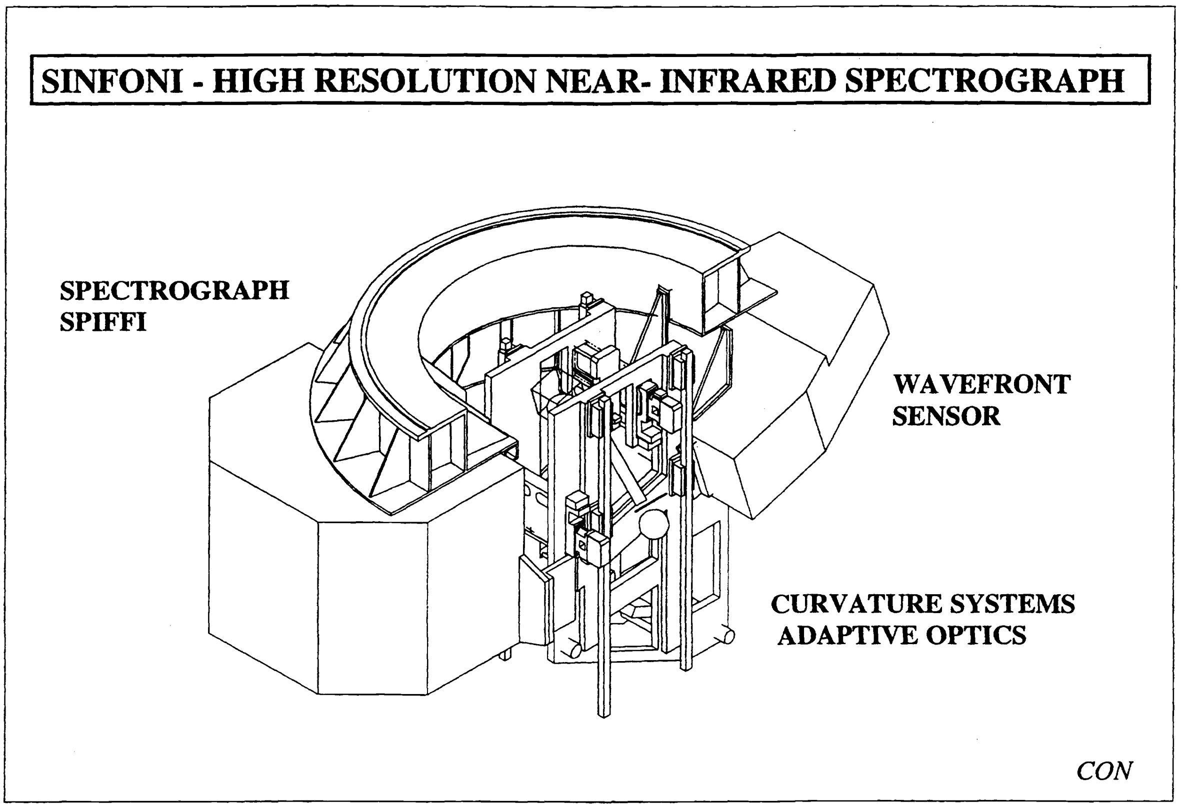

Figure 5. Two views of the MACAO optomechanics, for the main optical relay optics. A field of 2× 3 arcmin in the f/13.4 input beam is transferred to the f/17 cold focal plane of SPIFFI. The SPIFFI entrance window also acts as a dichroic to separate the visible light, reflected toward the WFS, from the NIR light.

4.3. MACAO Performance

The performances of MACAO are evaluated for two different performance parameters, the encircled energy and the Strehl ratio. Numerical and analytical simulations have been performed, for NGS and LGS.

When the integral field spectrograph, SPIFFI, is used with pixel scales Nyquist sampling the diffraction limit, the AO system has to deliver diffraction limited resolution images. The images may be boosted by deconvolution, and the AO performance parameter is the Strehl ratio. When SPIFFI is used at coarser sampling, e.g. 0.″125/pxl or 0.″25/pxl, if we assume there is no deconvolution, the relevant performance parameter is the long exposure encircled energy. Figures 7 and 8 show the performance with the NGS on axis, obtained with the numerical simulations.

Figure 9 shows the case of a LGS used to correct the high order image aberrations, and a tip-tilt NGS. The K-band Iso-Strehl ratio curves are plotted with the Strehl % value labeled, vs. tilt NGS distance in arcsec (y-axis) and tilt NGS V-magnitude (x-axis).

5. SINFONI

5.1. Instrument sensitivities

The SINFONI instrument has been designed to maintain a very high throughput (38%) at all wavelengths by using reflective optics wherever possible. As far as possible, cryogenic optics are used so that the thermal background from

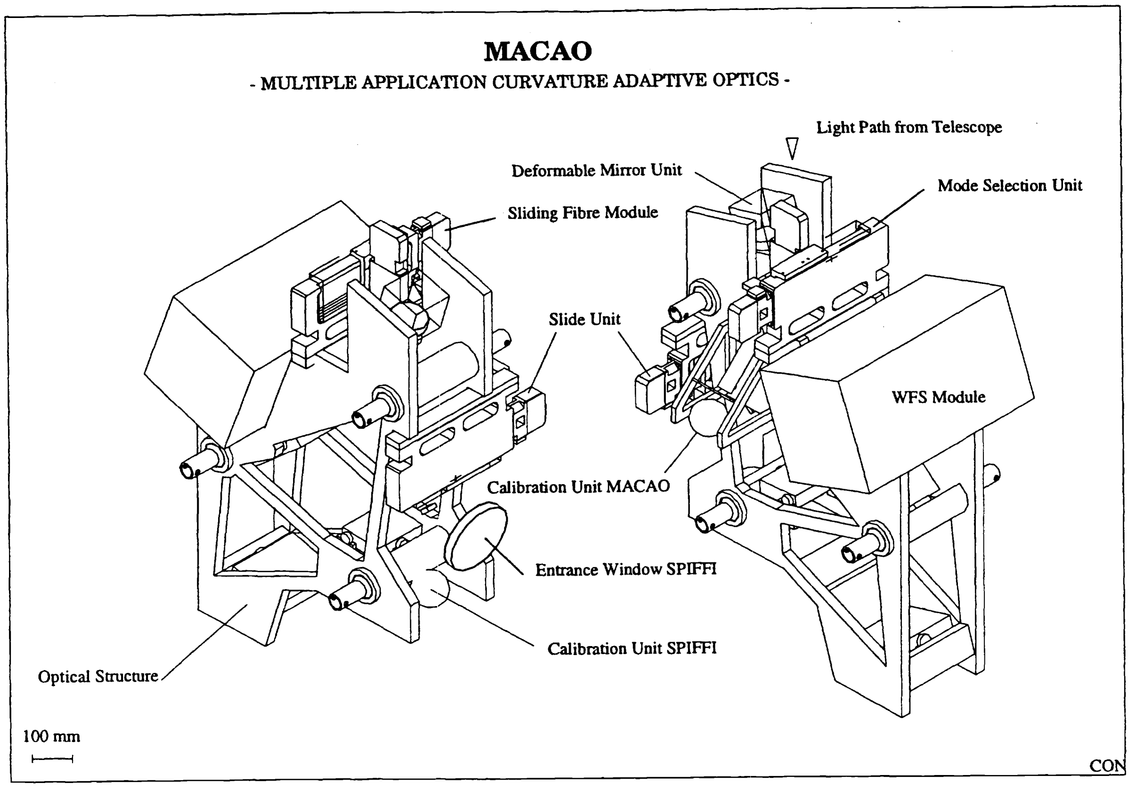

Figure 6. SINFONI mechanical interface, hosting SPIFFI and MACAO. SINFONI attaches directly to the Cassegrain Rotator Adaptor of the VLT.

the instrument is negligible compared to the contribution from the telescope and the sky. Additionally, cryogenic optics are placed in evacuated environments, keeping them clean and preserving their high reflectivities over long periods of time.

The instrument performance is mostly dictated by the specifications of the Rockwell HAWAII detector – each pixel has 0.1 $e^- s^{-1}$ dark current and 8 e^- read noise. The read noise contribution can be lowered by the use of long integration times and multiple reads, but the detector dark current is the limiting factor, especially at AO pixel scales and high spectral resolution, where the sky background per pixel is reduced to a very small value.

SINFONI will be used to observe a wide variety of scientific targets, and it provides many different modes which are optimized for various classes of objects. The tables below list the expected sensitivities of SINFONI for some typical cases, which would be of interest to the average observer. Sensitivities for other specialized applications may be computed by using the basic formulae.

The tables below are valid for the following constraints:

- Operation at the VLT (8 meter primary diameter).
- ON source integration time of 1 hour.
- Signal-to-noise ratio of 3 per spectral channel.
- Single frame exposure times longer than 240 seconds.

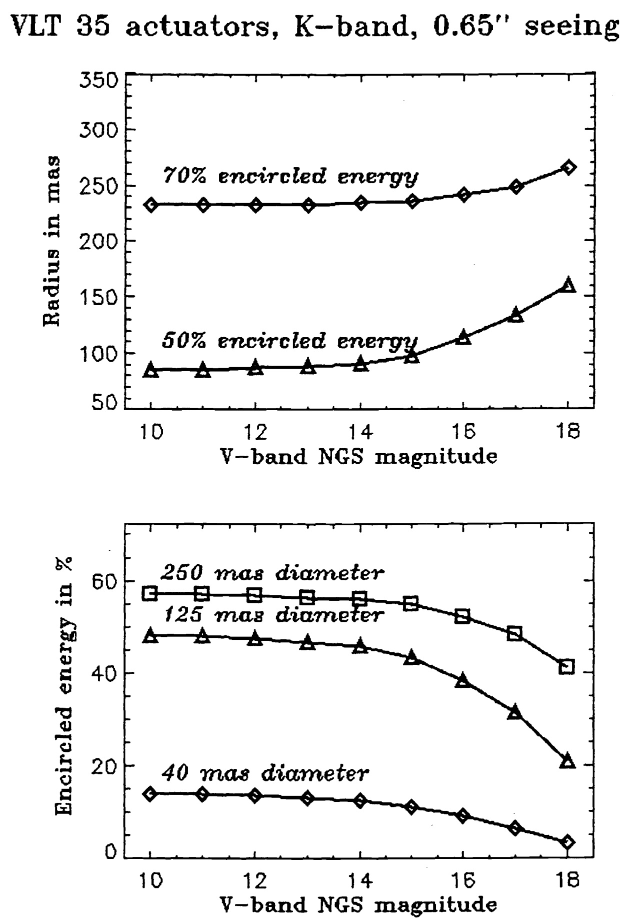

Figure 7. Encircled energy performance, median Paranal seeing, NGS on-axis.

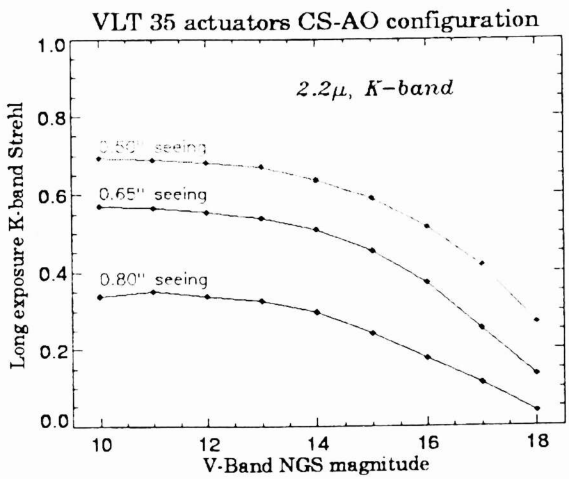

Figure 8. NGS K-band Strehl performance of MACAO for different seeing conditions, Paranal model atmosphere. NGS is on-axis.

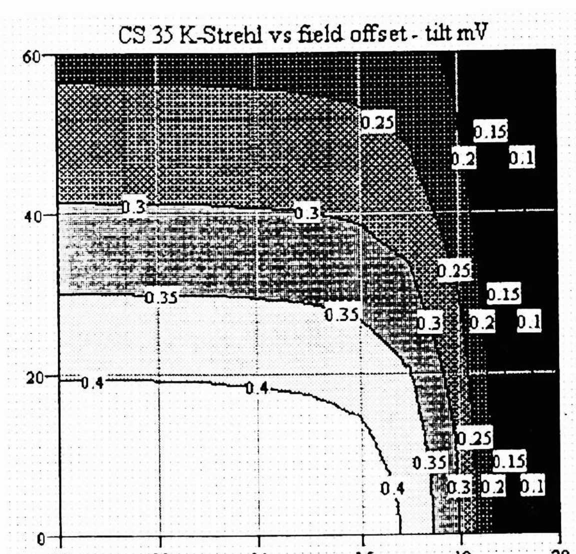

Figure 9. Iso-Strehl ratio curves, obtained with a 4.3 W LGS. The y-axis represents the tilt NGS distance from the target, in arcsec. The x-axis represents the tilt NGS V-magnitude.

5.2. Sensitivity to extended objects at high z

The object of interest is spatially extended (a normal galaxy) on scales of 1″, and at high z so that optical diagnostic lines (Hα or [O III]) are shifted into the near infrared. The observer is interested in either an integrated spectrum (for faint objects) or a spatially resolved spectrum at a R of 500. The observations are made at a R of 4500 in K and 4200 in H, in order to suppress the OH sky emission. Operation without the AO is foreseen, with pixel scales of 0.″25.

Table 1. SINFONI sensitivities to extended high z objects

	Source strength (ergs s^{-1} cm^{-2} Å^{-1})	
	H band	K band
Spatially resolved spectra (0.″25 pixels)	6.6×10^{-19}	9.6×10^{-19}
Integrated spectra	1.7×10^{-19}	2.4×10^{-19}

5.3. Sensitivity to point sources at high z

The typical object in this case is a QSO at high z whose rest frame optical spectrum is shifted into the near infrared. A spectrum at a spectral resolution of 500 is desired. The use of the AO system helps to increase the contrast of the object over the background. However, this leads to a sensitivity improvement only if the background still dominates over the dark current, which occurs only in the K band.

Table 2. SINFONI sensitivities to point-like high z objects

	Source strength (magnitudes)	
	H band	K band
Seeing limited	22.0	20.5
A.O. assisted	22.2	21.0

5.4. Sensitivity to bright objects in the nearby universe

The candidate objects in this case are bright nearby galaxies or star clusters, which the observer desires to study in detail at high angular and spectral resolution. Operation is at AO pixel scales, with spectral resolution of ~4500. The point source sensitivity is of interest for observations of the cores of globular clusters, faint companions in binary stellar systems or super-clusters in external galaxies. The extended source sensitivities are relevant to observations of Seyfert NLRs, ULIRGs, or the interaction zones of merging galaxies. High dynamic range is of importance here, and it is foreseen that some deconvolution will be applied to the data.

Table 3. SINFONI sensitivities to bright objects in the nearby universe

	Source strength	
	H band	K band
Extended objects (ergs s^{-1} cm^{-2} Å^{-1} $\square''^{-1}$)	2.7×10^{-16}	1.3×10^{-16}
Point sources (magnitudes)	21.0	19.8

5.5. Sensitivity to faint objects in the nearby universe

The objects under this category are faint sources which will be observed at 0.″25 pixel scales, with high spectral resolution. Sample projects include mapping the stellar velocity dispersions in the cores of normal galaxies (search for massive black holes), where the sensitivity to extended sources is relevant, and deep spectroscopy of the cores of open clusters, where the point source sensitivity is applicable. Although the sensitivity to point sources is worse than the previous case, a much larger field of view is covered in this mode.

Table 4. SINFONI sensitivities to faint objects in the nearby universe

	Source strength	
	H band	K band
Extended objects ($ergs\,s^{-1}\,cm^{-2}\,Å^{-1}\,\square''^{-1}$)	3.1×10^{-17}	4.6×10^{-17}
Point sources (magnitudes)	20.8	19.3

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REFERENCES

1. R. Hofmann, B. Brandl, A. Eckart, F. Eisenhauer, and L. Tacconi-Garman, "High angular resolution nir astronomy with large arrays (sharp i and sharp ii)," in *Infrared Detectors and Instrumentation for Astronomy*, A. M. Fowler, ed., *Proc. SPIE* **2475**, pp. 192–202, 1995.
2. F. Lacombe, O. Marco, F. Eisenhauer, and R. Hofmann, "First light on comic and sharp ii+," *ESO Messenger* **82**, pp. 16–17, 1995.
3. L. Weitzel, A. Krabbe, H. Kroker, N. Thatte, L. E. Tacconi-Garman, M. Cameron, and R. Genzel, "3d: the next generation near-infrared imaging spectrometer," *Astronomy and Astrophysics Supplement Series* **119**, pp. 531–546, 1996.
4. S. Anders, R. Maiolino, N. Thatte, and R. Genzel, "The aperture interchange module (aim): Diffraction limited nir spectroscopy with 3d and alfa," in *Infrared Astronomical Instrumentation*, A. M. Fowler, ed., *Proc. SPIE* **3354**, p. in press, 1998.
5. R. Bacon, G. Adam, A. Baranne, G. Courtes, D. Dubet, J. P. Dubois, E. Emsellem, P. Ferruit, Y. Georgelin, G. Monnet, E. Pecontal, A. Rousset, and F. Sayede, "3d spectrography at high spatial resolution i. concept and realisation of the integral field spectrograph tiger," *Astronomy and Astrophysics Supplement Series* **113**, p. 347, 1995.
6. M. Tecza, N. Thatte, A. Krabbe, and L. E. Tacconi-Garman, "Spiffi: A high-resolution near-infrared imaging spectrometer," in *Infrared Astronomical Instrumentation*, A. M. Fowler, ed., *Proc. SPIE* **3354**, p. in press, 1998.
7. D. Bonaccini, D. Gallieni, R. Biasi, F. Gori, M. Ghioni, C. Trottier, and N. Hubin, "Strap for the vlt instruments," in *Adaptive Optics and Applications*, R. K. Tyson and R. Q. Fugate, eds., *Proc. SPIE* **3126**, pp. 580–588, 1997.