The Aperture Interchange Module (AIM)
Diffraction Limited NIR Spectroscopy with 3D and ALFA

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ABSTRACT

The powerful tools of integral field spectroscopy and adaptive optics have made great contributions to the progress in astronomy in recent years. The combined use of these techniques now enables spectroscopy in the near infrared close to the telescope diffraction limit. This will provide new and interesting insights into a variety of objects such as AGNs, QSOs, circumstellar disks around highly extincted YSOs, etc.

Spectroscopy at or close to the telescope diffraction limit has some caveats which one has to be aware of when designing the instruments so as to maintain the maximum possible throughput and to optimize spectral resolution. Astronomical campaigns with our H - and K - band Integral Field Array Spectrograph 3D (Weitzel et al.[1]) in combination with the Laser Guide Star Adaptive Optics System ALFA (Hippler et al.[2] , Quirrenbach et al.[3] , Glindemann et al.[4]) at the 3.5-m telescope at Calar Alto require special observational techniques in order to make the most efficient use of the observing time available. Chopping by moving the telescope to do background subtraction makes it necessary to relock the A.O. system on the guide star after moving the telescope back to source. This procedure is usually rather time consuming. The Aperture Interchange Module (AIM), which we present here, enables us to perform chopping between source and blank sky while keeping the telescope fixed at a certain point in the sky. For this purpose AIM uses two different optical channels. The ON channel always points to the center of the 3$'$ALFA FOV, picking off a FOV of roughly 4$''$× 4$''$. With the OFF channel one can choose any offcenter position within the ALFA FOV execpt a central obscuration of 36$''$diameter. The AIM optics are designed in such a way that the optical pathlengths for the on and off- axis positions are kept equal. AIM also includes a scale changer which magnifies the scale from 0$''\!.$25 / pix to 0$''\!.$07 / pix. The 3D spectrometer itself is equipped with two interchangeable grisms, so that one can choose between H- and K- bands and between spectral resolutions of 1100 and 2100. The commissioning run of AIM together with 3D and ALFA took place in July 1997 at the 3.5m Calar Alto telescope.

Keywords: Near Infrared, Observations, Integral Field, Spectrographs, Adaptive Optics, Diffraction Limit

1. INTRODUCTION

1.1. Advantages of Coupling Integral Field Spectrometers with A.O. systems

The advantage of integral field spectrometers like 3D with respect to conventional long slit spectrographs is the possibilty to take a spectrum of a two dimensional field on the sky in a single exposure. This increases time efficiency and eliminates the problem of changing atmospheric conditions when observing different regions of an extended object. On the other hand, adaptive optics systems provide high spatial resolution for ground based systems, even extending close to the telescope diffraction limit.

These advantages multiply when both systems are combined. The whole FOV now gets atmospherically corrected at the same time, offering reliable results, which are highly spectrally and spatially resolved. Furthermore, observations using A.O. systems are in general more time consuming due to locking on appropriate guide stars (see also section 2.2) and setting up and initializing the correction algorithms, making the application of time efficient integral field spectroscopy even more reasonable. The biggest advantage is that one can fully sample the point spread function of the A.O. system, because it is possible to image a two dimensional field. With a long slit spectrograph, one could have problems disentangling P. S. F. effects and positioning the slit.

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1.2. Scientific Justifications

Integral field spectroscopy, in combination with an adaptive optics system, can completely revolutionize our understanding of a wide variety of astromonical problems. In the next paragraph, we briefly describe two open questions where ALFA/AIM/3D could have a major impact.

How ubiquitous are central black holes in galactic nuclei ? In the last few years, a variety of techniques (masers - Miyoshi et al 1996[5] , rotating gaseous disks - and stellar dynamics - Kormendy et al 1995 [6] , 1997[7]) have been used to probe the dark masses lurking at the centers of galaxies. The accuracy of the mass estimate depends critically on the distance from the center at which the velocity dispersion is measured - the impact of AIM will be to improve the spatial resolution by almost an order of magnitude. In addition, the use of near - IR stellar absorption features (Gaffney et al. 1995[8] , Lester et al. 1994[9] , Doyon et al. 1994[10]) will permit the present stellar dynamics techniques to be extended to normal spiral galaxies, where extinction may prevent measurements at visible wavelengths. The need to disentangle rotation effects from true velocity dispersion, as well as tests for dispersion anisotropies makes our integral field capacity a necessary improvement over long slit techniques.

What is the nature of QSO host galaxies ? Although it is now clear that QSO host galaxies are omnipresent (McLeod & Rieke 1996[11] , Bahall et al. 1996[12]), the nature of these galaxies has, so far, only been studied using broad band imaging. Narrow band images in filters centered on prominent emission lines like $H\alpha$ + [N II], [O III] etc. would yield enormous information on the nature of these hosts, their level of star formation activity, their gas content and their evolutionary history. Due to the large range of redshifts which need to be covered, spectroscopy with significant wavelength coverage is required. In addition, integral field capacity is a must, since it is the two - dimensional morphology of the hosts which is of interest. The light concentration and high resolution possible via the use of adaptive optics makes ALFA/AIM/3D a unique instrument combination to tackle this open question. The QSO provides a convenient tip - tilt reference making this project a perfect match to our instrumental capabilities.

2. INSTRUMENTAL SETUP

2.1. Slit Diffraction Effects

When operating our integral field spectrometer at or close to the telescope diffraction limit, the effect of slit diffraction at the image slicer becomes important. As a result, the convolution of the telescope pupil and the fourier transform of the slit leads to a pupil pattern on the grating surface which is blurred and has a larger size that one derived using geometrical optics calculations. This has some consequences for the instrumental design.

First, a cold stop at the standard grating position is not sufficient to block thermal background. Instead, it is necessary to put a cold stop in an intermediate pupil plane before the slit.

Second, slit diffraction causes a decrease in the f - number of the beam beyond the slit, i. e. within the spectrometer. Thus there is a need to oversize the spectrometer optics in comparison with geometric ray tracing in order to not lose much light. (Some will be lost in any case, since lenses are not infinitely large). Since our spectrometer is designed for a maximum pixel scale of $0\farcs5$ / pixel, it already sufficiently oversized for operation close to the diffraction limit.

2.2. Observational Techniques

Operation of our Integral Field Array Spectrograph 3D in combination with the Adaptive Optics System ALFA at the 3.5-m telescope at Calar Alto makes it necessary to develop a special observation technique in order to make the most efficient use of the observing time available. Usually background subtraction is done by moving the telescope away from the source and taking an image of the blank sky. When one applies this procedure repeatedly using an A.O. system then it is necessary to relock the system on the guide star every time when moving the telescope back to the source. This is generally rather time consuming and reduces observing efficiency.

An alternative idea is to use two subapertures within the ALFA FOV. One of these apertures contains the object and the other blank sky. If one succeeds in keeping the optical pathlengths for the two subapertures equal, then the only difference in pathlength comes from the telescope and the A.O. system, which results in different background and throughput. In order to compensate for this one moves the telescope so that the source moves from one subaperture to the other and then repeats the integration. This procedure is illustrated in Fig. 1.

By appropriate mathematical transformations of the images of the two subapertures it is possible to remove their differences in background and extract the intensity of the source. Using two subapertures, one has to move the telescope and relock the A.O. system on the guide star only once.

A short calculation demonstrates this.

If the source is in the central subaperture then the total intensity $i^{(1)}_{central}$ consists of

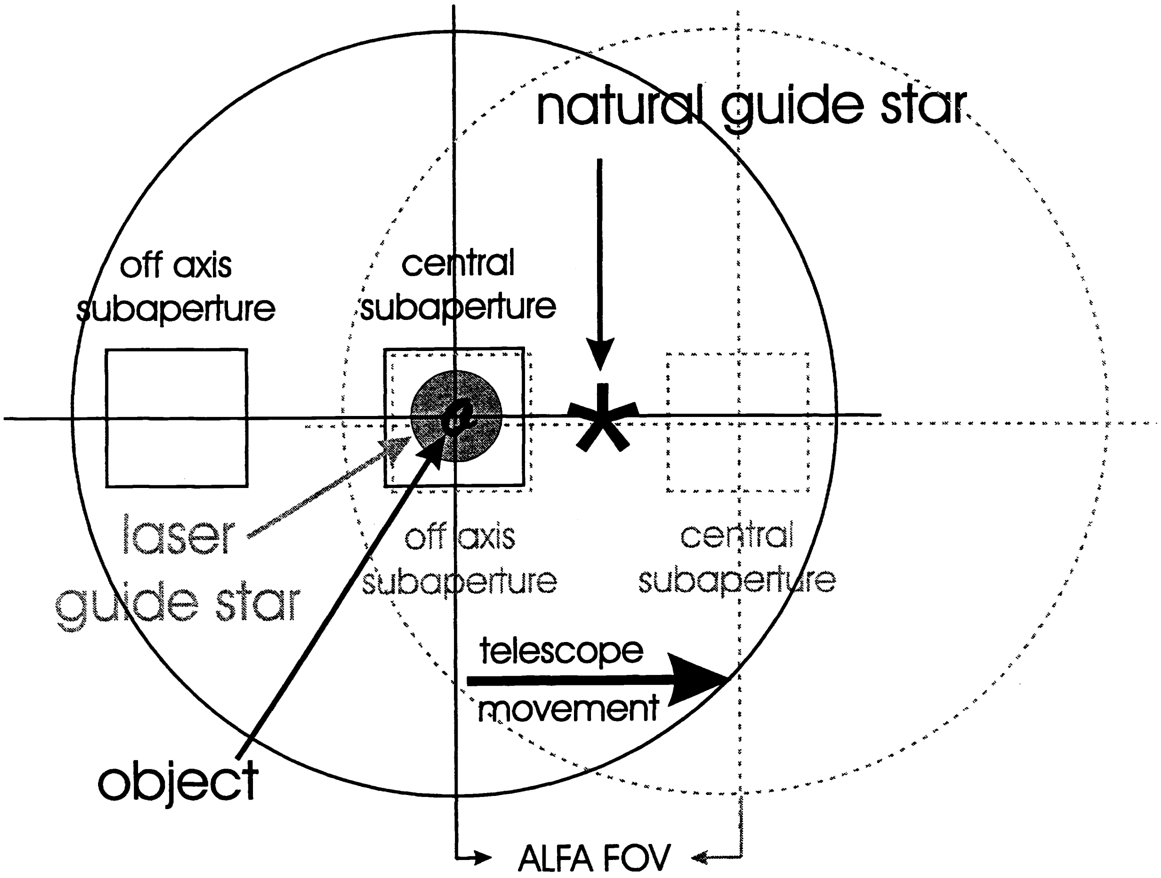

Figure 1. Schematic illustration of observation mode

$$i^{(1)}_{central} = s_{central} + b^{source}_{central} + T_{central} \tag{1}$$

where $s_{central}$ is the source intensity in the central aperture,
$b^{source}_{central}$ the corresponding sky background around the source and
$T_{central}$ the background contribution from the path of the telescope and the A.O. system associated with the central aperture.
The intensity in the off axis subaperture containing blank sky $i^{(1)}_{offaxis}$ composes of

$$i^{(1)}_{offaxis} = b^{blank}_{offaxis} + T_{offaxis} \tag{2}$$

where $b^{blank}_{offaxis}$ is the background of the blank sky picked up in the off axis aperture and
$T_{offaxis}$ the background contribution from the path of the telescope and the A.O. system associated with the off axis aperture.
If $i^{(1)}_{offaxis}$ gets subtracted from $i^{(1)}_{central}$ then the result is

$$s_1 = i^{(1)}_{central} - i^{(1)}_{offaxis} = s_{central} + (b^{source}_{central} - b^{blank}_{offaxis}) + (T_{central} - T_{offaxis}) \tag{3}$$

Now we move the telescope, so that the off axis aperture contains the source, and repeat the integration. Therefore, the intensity consists of:

$$i^{(2)}_{offaxis} = s_{offaxis} + b^{source}_{offaxis} + T_{offaxis} \tag{4}$$

where $s_{offaxis}$ is the source intensity in the off axis aperture and $b^{source}_{offaxis}$ the corresponding sky background around the source in the off axis aperture. The central subaperture now points towards blank sky. Therefore we get:

$$i^{(2)}_{central} = b^{blank}_{central} + T_{central} \tag{5}$$

where $b^{blank}_{central}$ is the background of the blank sky picked up in the central aperture.

Subtraction of $i^{(2)}_{central}$ from $i^{(2)}_{offaxis}$ leads to

$$s_2 = i^{(2)}_{offaxis} - i^{(2)}_{central} = s_{offaxis} - (b^{blank}_{central} - b^{source}_{offaxis}) - (T_{central} - T_{offaxis}) \tag{6}$$

It is reasonable, to assume that

$$\begin{aligned} b^{source}_{central} &= b^{blank}_{central} & (7) \\ b^{source}_{offaxis} &= b^{blank}_{offaxis} & (8) \end{aligned}$$

If we add up s_1 and s_2 then the only terms left are the intensities related to the source.

$$s = s_1 + s_2 = s_{central} + s_{offaxis} \tag{9}$$

To realize this concept, we designed the Aperture Interchange Module (AIM), whose optical layout is shown in Fig. 2. This instrument is a module which couples ALFA and 3D. It enables the observer to pick two 4″× 4″apertures within the 174″A.O. FOV and fold them into the spectrometer.
Using AIM, it is possible to observe at two different pixel scales. The smaller one, designed for diffraction limited observations, is 0.″07 / pix, since the FWHM of the Airy pattern delivered by the 3.5 m - telescope at 2.2 μm is 0.″14. The total FOV is 1.″12 × 1.″12. The larger one is 0.″25 / pix, which corresponds to a 4″× 4″FOV. This pixel scale is used for observations using tip - tilt only, for faint objects and for acquiring of the source.

2.3. The Aperture Interchange Module

A detailed drawing of the optical design for choosing the two subapertures within the ALFA FOV is shown in Fig. 3. The first aperture is always at the centre of the ALFA FOV and the second one can be choosen anywhere within the ALFA FOV (with the exception of the center of course). By flipping a mirror (ON - OFF mirror) in and out of the optical beam one can direct either the central or the off axis aperture into the spectrometer. This interchanging of the apertures can be done within five seconds. The optical pathlengths of both apertures stay the same for all positions within the ALFA FOV.
The observer selects the appropriate off axis field by moving a zinc sulfide prism in r,θ coordinates in a plane parallel to the ALFA focal plane. The centre of the r,θ coordinate system, which is identical to the home position of the prism, is on the optical axis of ALFA. The prism itself is located 10 mm under the ALFA focal plane.
The beam associated with the selected off axis aperture enters the prism through its hypotenuse surface. Then it gets folded by total internal reflection on the two prism surfaces so that it coincides with the optical axis. After leaving the prism through its hypotenuse surface the beam gets folded by 90 degrees by a flat gold coated mirror. At the position of the ON - OFF mirror the off axis rays meet the rays coming from the center of the ALFA FOV. The latter ones get folded to this point by three gold coated mirrors. By moving the ON - OFF mirror, one can fold either the on axis beam or the off axis beam into the relay system.
The relay has a magnification of 1 : 3.8, which corresponds to a pixel scale of 0.″25 /pix. It consists of a positive barium fluoride lens and a concave gold coated spherical mirror. The 0.″07 pixel scale is achieved by moving a 1 : 3.6 Galilean telescope into the collimated beam. This little telescope consists of a positive barium fluoride lens and a negative zinc selenide lens. A cold stop, placed at the intermediate pupil plane between the two lenses of the Galilean

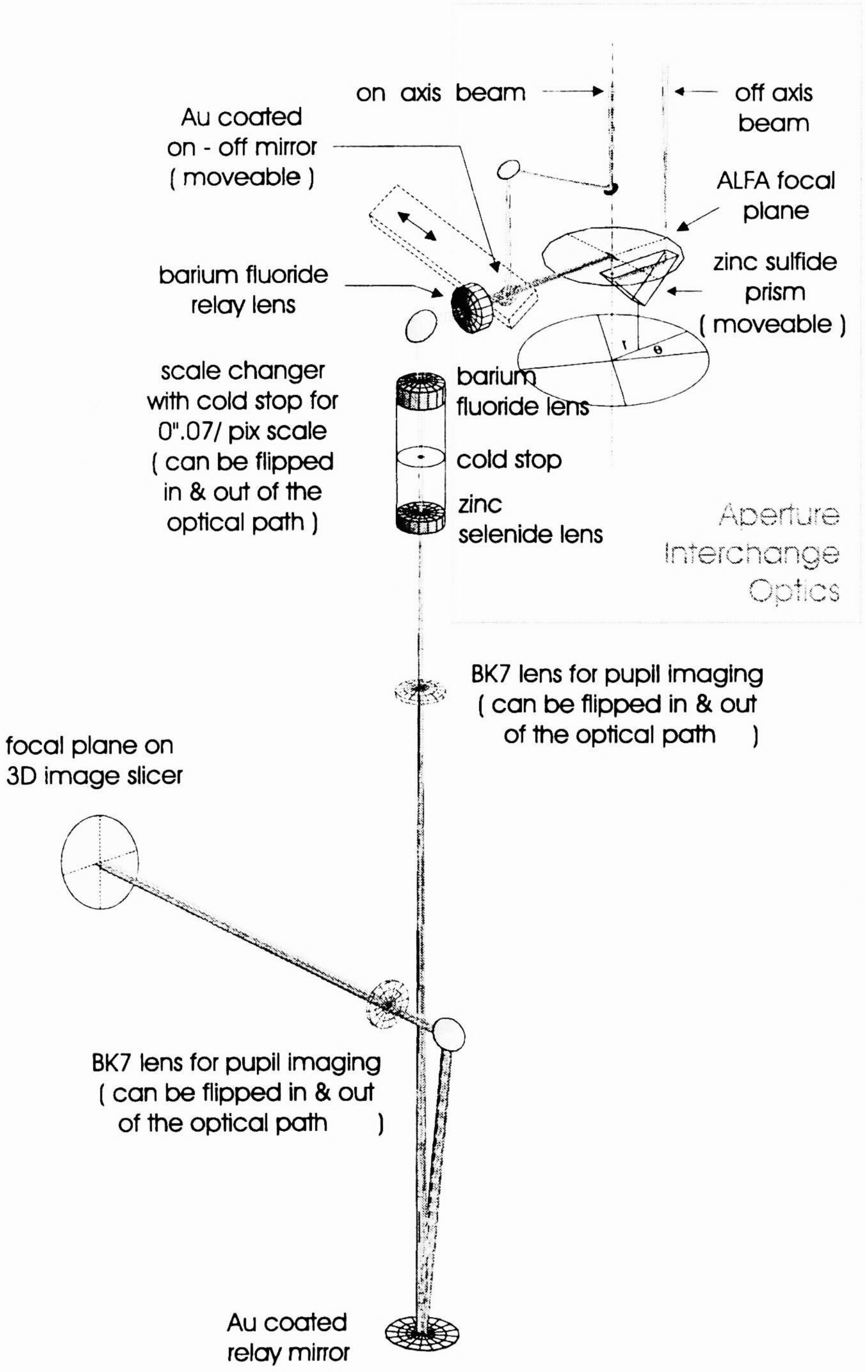

Figure 2. Optical layout of the Aperture Interchange Module

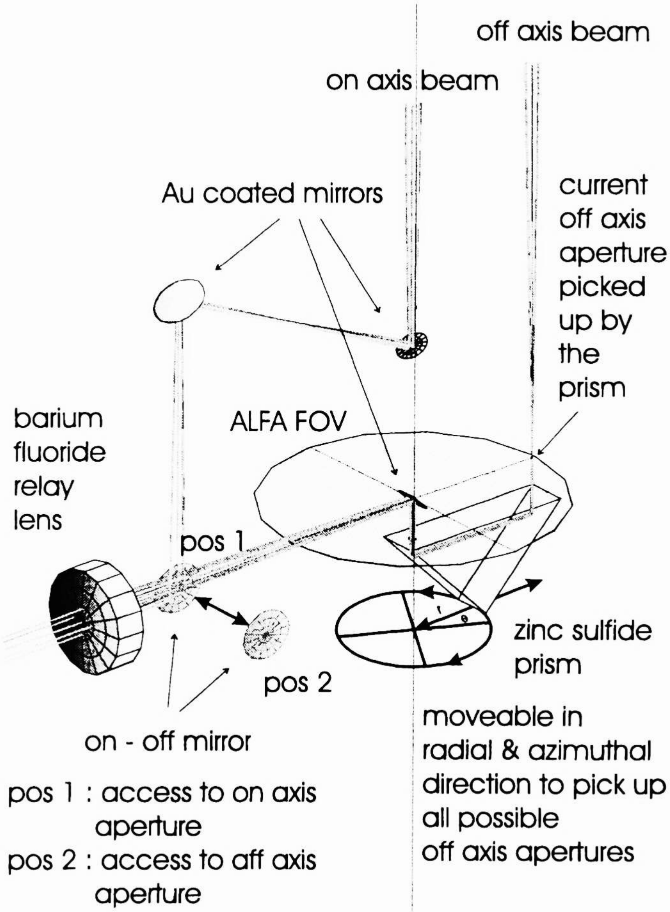

Figure 3. Detailed drawing of the Aperture Interchange Optics

telescope, blocks thermal radiation one would pick up when switching from the 0.″25 to the 0.″07 pixel scale.
The intermediate pupil plane created by the collimator lens has a diameter of 3.38 mm in the 0.″07 / pix scale. This makes alignment of the cold stop placed in the Galilean telescope rather critical. In order to ease the alignment procedure, one flips two BK7 lenses into the optical path, which interchange the corresponding focal and pupil planes. This means that the pupil plane now comes to lie at the position of the image slicer and the focal plane at the grism position. Therefore, one has at the detector plane the dispersed sliced image of the pupil. With the 3D software it is then possible to see the restored image of the pupil on the screen. Any vignetting caused by a misalignment of the Galilean telescope and of the cold stop with respect to the pupil can now be easily detected. The pupil imaging optics consequently provides a very powerful tool for easy alignment of the cold stop with the pupil.

2.4. The 3D Spectrometer

The Integral Field Array Spectrograph 3D has already been described in Weitzel et al. 1996[1] , so only a short summary of its concept and its properties is given here. The optical design of 3D is shown in Fig 4.
The image slicer divides the two dimensional image provided by the telescope into 16 strips along one spatial dimension and rearranges them so that they form a step pattern, which can be identified as a long slit. The pupils of all 16 strips coincide, so that a common one is formed. The image slicer consists of two mirror systems. The first one is a stack of 16 gold coated rectangular shaped flat mirrors, 8 mm in length and 0.4 mm in height. The surface normals of these 16 mirrors are rotated by small angles (4 to 1.75 degrees) with respect to each other. The second mirror system is an arrangement of 16 flat mirrors positioned along an hyperbola.

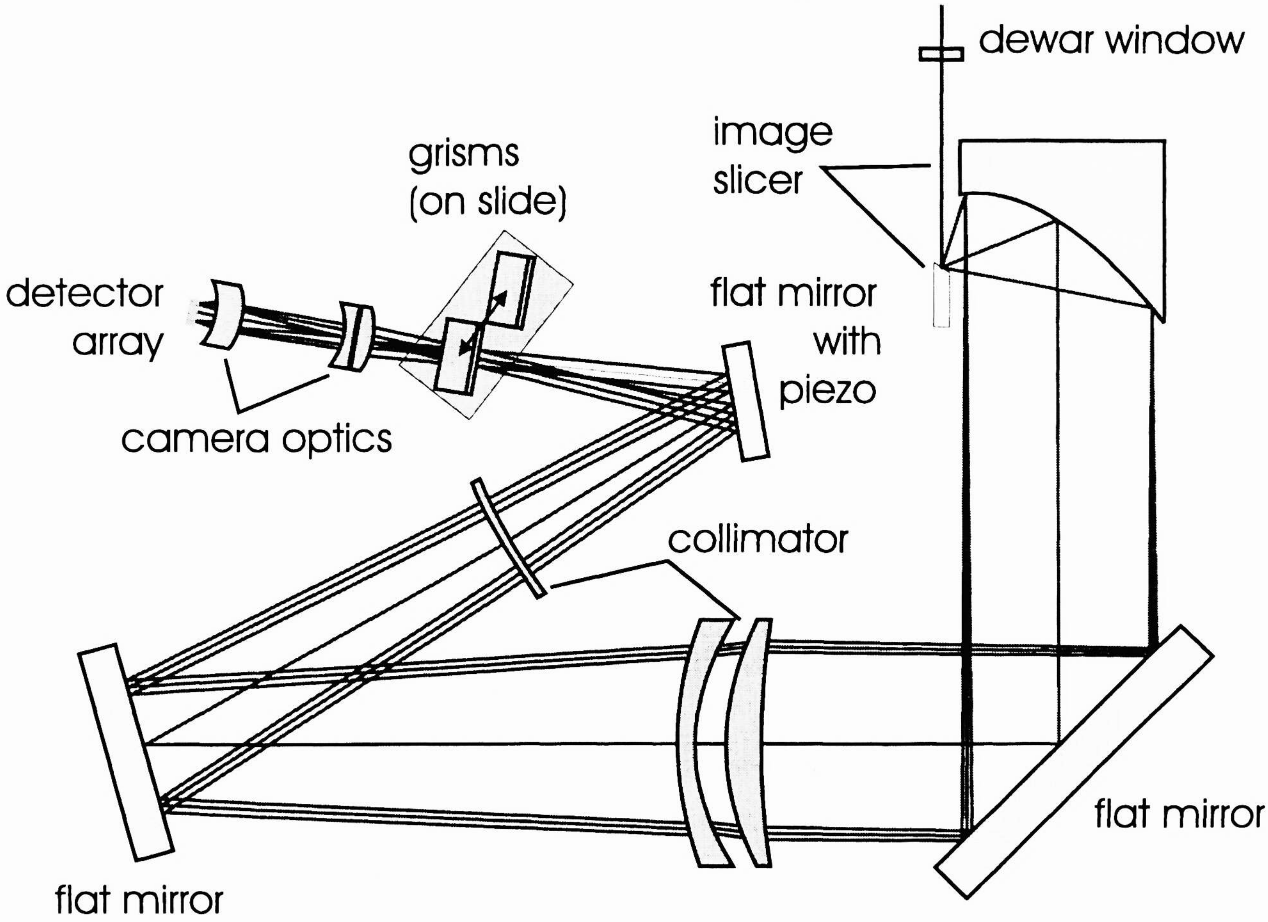

Figure 4. Optical Layout of the 3D Spectrometer[1]

The long slit formed by the slicer enters the collimator system consisting of one barium fluoride lens and two calcium fluoride lenses. The dispersing element is a transmission grating (grism) operating in Littrow configuration. The spectrometer is equipped with two grisms mounted on a slide, so that they can be interchanged during an observation. There are grisms available for the H - and K - band with a spectral resolution of 1100 or 2100. The grisms are made of KRS5. The camera is made up of two zinc sulfide lenses and one calcium fluoride lens. The detector is a 256 × 256 HgCdTe NICMOS III array. This means that each of the 16 strips again get divided into 16 pixels.

As a result the incoming image gets split into 16 resolution elements in both spatial directions. The number of pixels in the spectral dimension is 256.

With the exception of the image slicer and the first flat mirror after it, all the optics work in a cryogenic environment at 77 K in order to minimize thermal background radiation.

3. RESULTS AND DISCUSSION

3.1. Optical Quality

For determination of the point spread function of the combined system of ALFA, AIM and 3D, we put a silica fiber with a core diameter of 10 μm, corresponding to $0\farcs06$ on the sky, at the focal plane of the telescope. The fiber works monomode for wavelengths in the near infrared region. The FWHM of the Airy pattern is $0\farcs14$ projected on the sky. Therefore the FWHM of the convolved image corresponds to $0\farcs14$.

In Fig. 5 the measured point spread functions are shown as a three dimensional surface plot. The upper row contains the results for the $0\farcs25$ / pixel scale. In the left corner is displayed the P.S.F. for the optics imaging the central part of the ALFA FOV. The corresponding result for a position with a distance of $62\farcs8$ from the center is shown in the

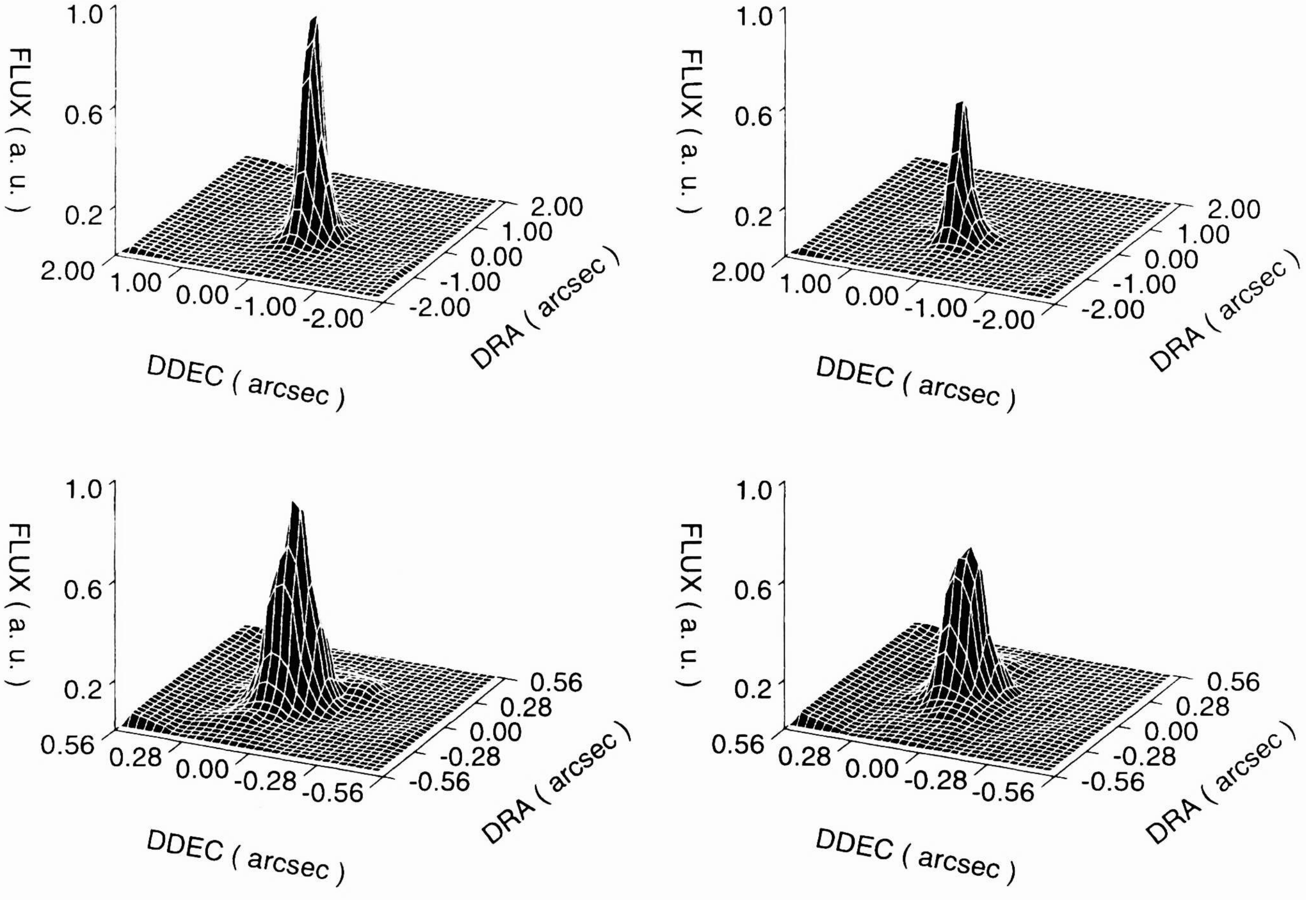

Figure 5. Point spread functions of the combined system of ALFA, AIM and 3D. The upper row shows the P.S.F. for the 0 ″.25 / pixel scale. As a source a fiber with a core diameter of 10 μm has been used. The result for the optics imaging the central ALFA FOV is shown in the upper left corner. The result for an off center position can be studied in the upper right corner. The corresponding results for the 0 ″.07 / pixel scale are shown in the lower row.

upper right corner. The magnification of the combined system is 0.95 for this pixel scale. Therefore the P.S.F. is undersampled, so that a useful determination of the FWHM is not possible here.
In the lower row of Fig. 5 the measurements for the 0″.07 / pixel scale are shown. The point spread function for the central position is on the left and that for an off center position (same distance from the center as for the 0″.25 scale) on the right side. The magnification of ALFA/AIM/3D is 3.24, so the P.S.F. is well sampled. The FWHM of these images is 0″.14, which corresponds well with the calculated values.

3.2. First Observational Results

In July 1997 we successfully commissioned the combined instrumental system ALFA/AIM/3D. Despite a number of optimisations needed for ALFA, which were still incomplete at that time, we got a number of reasonably promising results. One of these is presented in Fig. 6, which shows the effect of various levels of A.O. corrections while observing the single star HR 8667 (V = 3.95). The left picture shows the image of the star, corrected with tip tilt only, whereas the right one shows the improvements possible at that time when using the A.O. system. The measurements were done with the 0″.07 / pixel scale.

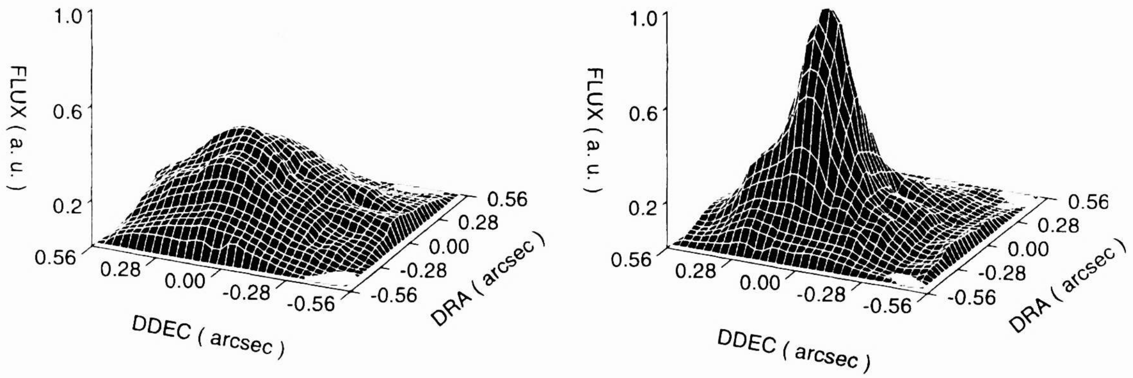

Figure 6. 3D image of the Star HR 8667 (V = 3.95, G8), taken with ALFA/AIM/3D at the 0″.07 / pixel scale. The image on the left shows the object taken with tip tilt correction only, the one on the right the result acquired with full A.O. correction.

4. CONCLUSION

We presented the instrumental setup for performing diffraction limited near infrared spectroscopy with our Integral Field Spectrometer 3D in combination with the Adaptive Optics System ALFA. For this purpose an additional instrument, the Aperture Interchange Module (AIM) has been designed. The instrument is optimized with respect to spectral resolution, light throughput and time efficiency while observing at the telescope.

First measurements have shown that the optical design fulfills the theoretical expectations concerning image quality, and the first astronomical observations were encouraging.

The next campaigns with ALFA/AIM/3D are foreseen to take place in June and July 1998, where a vastly improved ALFA system will allow scientifically valuable observations.

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