IJAF - Instrumentcenter for Jordbaseret Astronomisk Forskning
Astronomisk Observatorium, Juliane Maries Vej 30, DK-2100 København Ø, Danmark.

Astronomical Instrument Centre

Report #3: *HiRAC-II*, a 5-mode adaptive optics system for NOT

by

Michael I. Andersen & Anton Norup Sørensen
Copenhagen University Observatory

March 3. - 1996

1 Introduction

HiRAC is now installed at the NOT, though some work still need to be done before it is fully operational. During the last half year, we have obtained a far better description of the behavior of the atmosphere above La Palma, both during the seeing campaign in november, but also during commissioning of *HiRAC*. The understanding is now that image motion is significantly reduced due to an outer scale length of turbulence of ≈5-8m, while atmospheric focus and astigmatism terms remains essentially unaffected.
A much improved understanding of the site and telescope has also been obtained. In our analysis of image quality on the NOT [Andersen & Sørensen 96], we have shown that it should be possible to obtain a median image quality of $0''.40$ with *HiRAC*, during the good observing season, provided the performance of the telescope is optimized.
When we started out on *HiRAC*, an upgrade to a 5-mode system was foreseen. At that point, we considered a median image quality of $0''.48$ with 5-mode correction in the V-band as a realistic goal. With the present knowledge,it is clear that this goal is far too pessimistic.

2 Expected performance

In estimating the performance of a 5-mode AO system, we assume that the telescope performance have been improved corresponding to that of 'phase 4' in [Andersen & Sørensen 96]. We adopt a median seeing of $0''.39$, which result in a passive image quality of $0''.43$, taking into account the remaining imperfections of the telescope. We then compute a large number of PSF's, each based on a sum of an atmospheric wavefront and remaining telescope aberrations. In fig. 1, we show the radial profile of the average PSF. The shape of the PSF changes radically by 5-mode correction, with a build up of a diffraction limited core. As an objective measure of the image quality, we give the *Strehl equivalent seeing*, which is the raw seeing scaled by the inverse square root of the relative Strehl ratios, i.e. if the peak intensity is improved by a factor of four the Strehl equivalent seeing is reduced by a factor of two. We do not include servo loop errors, implying that the result is overestimating the the improvement in image quality. Realistic values for the typical image quality is likely to be $0''.30$ in V and $0''.20$ in I.
In the November seeing campaign, the correlation time of focus and astigmatism was measured, giving typical values of 0.1 sec. Under these conditions, we should expect to run the servo loop at 50Hz or faster. This suggest a limiting magnitude for the WFS of ≈15. We do not have measurements of the isoplanatic patch. We expect it to be of the order of $30''$, resulting in a sky coverage of ≈10% at the galactic pole and ≈50% at the equator.

3 The suggested concept for *HiRAC-II*

We think that we have been quite success full by using the 'adjustable prism' concept in *HiRAC*. We have not encountered major problems with this technology, as one could a priori have expected. The advantage of using a transmitive adaptive optics element is, that we do not need an intermediate focus, implying that the number of optical elements can be minimized.
For 5-mode correction we propose to use 'adaptive lenses', where plane parallel glass plates are deformed by piezo electric elements. A diagram of the proposed corrector is shown in fig. 2.

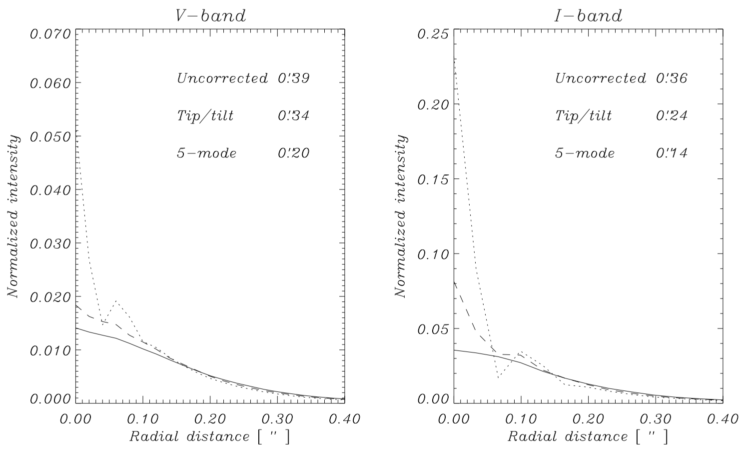

Figure 1: Radial profile of uncorrected (full line), tip/tilt corrected (dashed) and 5-mode corrected PSF in the V and I band. The Strehl equivalent seeing for each degree of correction is given.

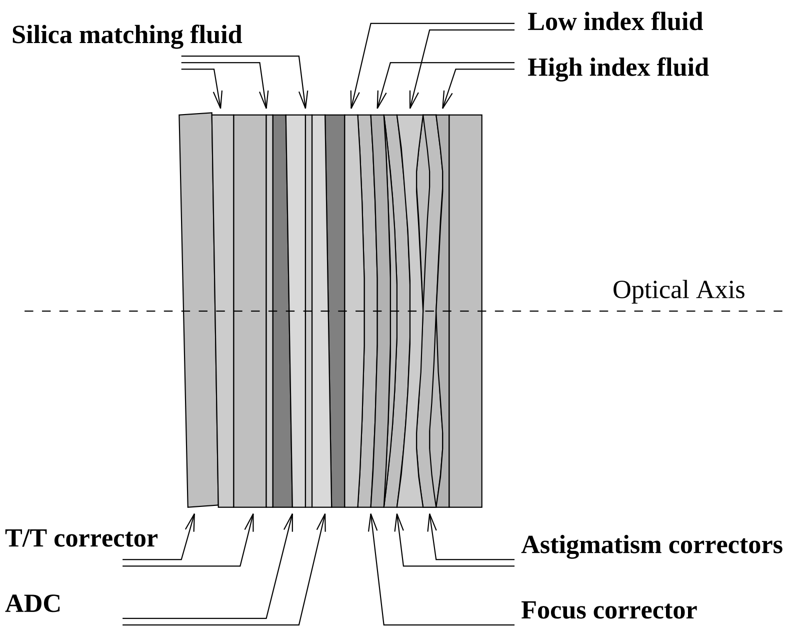

Figure 2: *HiRAC-I* incorporates only the tip/tilt corrector (the first two glass plates). In addition, the 5-mode corrector must have one element for correcting focus and two elements for correcting astigmatism. Shown here is also an embedded Atmospheric Dispersion Corrector (ADC) consisting of two prisms which can be rotated around the optical axis.

Deformable glass plates are immersed in optical fluids. The corrective effect is achieved by using fluids having different index of refraction on each side of a glass plate. Integrating all corrections in the same unit, we avoid having more than two air/glass interfaces for the complete corrector. Thereby through put will be kept at a level of 90% of a direct CCD. A disadvantage of this

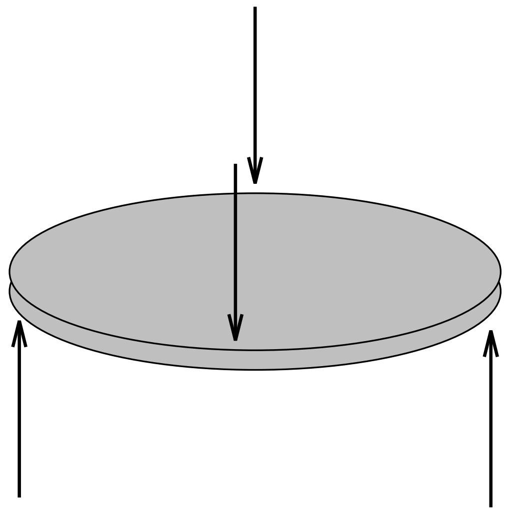

Figure 3: The astigmatic correction is obtained by applying forces at the edge of a glass plate in four points. The glass plate is deformed into a saddle shaped surface, representing that of a Zernike astigmatism term. Any orientation of the astigmatism correction can be obtained by having two correctors, of which one is rotated by 45 °around the optical axis, with respect to the other.

approach is that we need rather large strokes of the corrector. The advantage of this is that we expect an encoding accurate to $\approx\lambda/50$ for each mode of correction. We have made preliminary experiments, from which we were unable to detect any limitations in the mechanical transfer function.

We have tested the four point deformation of a glass plate, mounted in an aluminum ring into a Zernike astigmatism shape. We find that the RMS deviation of the glass plate is within 1% of the amplitude of the deformation. We therefore consider the astigmatism corrector as fairly easy to realize. The best choice of actuator is likely to be piezo elements. The sign of the astigmatism correction will change continuously, and the actuators will therefore have to be operated in a push-pull system, implying that eight piezos will be needed for each corrector. The deformation of the focus corrector is obtained by applying a pressure difference between the fluids on each side of the glass plate. A pair of piezo driven pistons in a push-pull configuration are presently considered as the best choice of actuator for the focus corrector.

With the expected image quality, differential atmospheric refraction will become a very important issue. We suggest implementing an ADC as part of the adaptive corrector, since we in this way avoid having further losses.

A 2 by 2 element Shack-Hartmann WFS, with some modifications, is foreseen. It is very simple to realize, because we may simply add a pyramid to the present guide probe in *HiRAC*, splitting the beam into four segments. In practice, one system for T/T guiding and one four segment WFS should be available. These can be implemented on a carriage, allowing the observer to change from T/T correction to 5-mode correction whenever desired.

4 Manpower and hardware cost

We will outline a preliminary budget for a *HiRAC-II* as far as we have been able to estimate hardware and manpower costs. Manpower, including workshop time is given in table 1. The hardware budget is given in table 2. Table 1 do not include project management, test of prototypes and implementation of the instrument at the telescope.
Within the present budget of the instrument center at Copenhagen Observatory, we do not have the necessary funding for the project. We consider this a subject of discussion with NOTSA, if the project is considered of interest to the community.

Table 1: Expected work load in man months

	Electronics	Mechanics	Software
Development of corrector prototype	1	3	1
Development of WFS prototype	1	1	1
Fully operational corrector	2	3	2
Fully operational WFS	1	2	1
Atmospheric dispersion corrector	1	2	1
Total	6	11	6

5 Time scale for development and implementation

It is expected that development and test of prototypes will take 6 months. First of all it is critical, that a feasibility study is made as soon as possible. Integration of the instrument will take another 6-8 months, and lab tests 4 months from completion of hardware. These phases can be partly overlapping, but we should expect $\approx$18 months of work before we are ready for test at the telescope. Another half year of work should be expected for integration and error correction at the telescope.

6 Adaptive optics and an instrument plan for the NOT

When suggesting *HiRAC-II*, we focus our attention at adaptive optics (AO) for high resolution optical imaging. It is however reasonable to look at AO for the NOT in a more general context. We consider AO at the NOT relevant for

- Optical imaging and low resolution spectroscopy.
- Near IR (non thermal) imaging and spectroscopy.

Table 2: Estimated hardware budget for *HiRAC-II* in Dkr.

Prototypes:	
Optics for corrector	15000
Mechanics	5000
Piezo elements 8 pcs.	40000
Electronics	10000
Total	70000
Operational instrument	
Optics	60000
Mechanics	20000
Piezo elements, 16 pcs.	80000
Electronics	30000
Total	190000

- Visible and near IR high resolution spectroscopy for optimum throughput.

whereas adaptive optics in the thermal IR have little relevance for the NOT because the telescope/atmosphere is essentially diffraction limited at these wavelengths. What do this then imply for adaptive optics for the NOT in a more general context. We can think of two different approaches for the implementation of adaptive optics:

- An adaptive optics module which is part of an instrument, as in the case of *HiRAC*.
- An adaptive optics module which is an integral part of the telescope. This could be implemented as part of the adaptor or in the secondary mirror.

Seen from an adaptive optics point of view, the implementation of an adaptive optics module in the instrument adaptor is the best solution, because we can place the corrective element at the conjugate plane of the turbulent layers (the lower atmosphere). From an optical point of view, implementation at the secondary unit is the best solution, because the number of extra optical elements in minimized in this way. Finally, implementing the adaptive optics as part of the instrument offers the advantage, that it is a stand alone system, which can be optimized for the specific application. This approach is only reasonable as long as the adaptive optics system is not considerably more expensive than the instrument it self, i.e. as long as we consider low order AO.

Strictly speaking, *HiRAC* is not an instrument in itself, but rather an extension to the adaptor, containing filter unit and guiding system. We may therefore in principle exchange BroCamII, which is now mounted on *HiRAC*, with another instrument, like ALFOSC or an IR camera.

The performance of low order adaptive optics in the near IR have been simulated, adopting the same conditions as used for the V and I band simulations. We show the corresponding radial

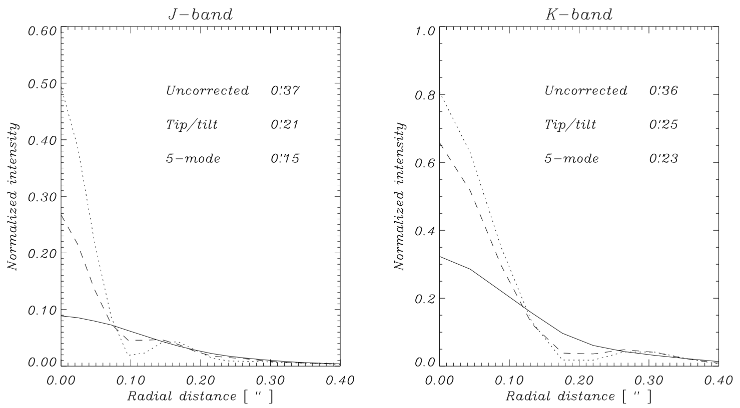

Figure 4: Radial profile of uncorrected (full line), tip/tilt corrected (dashed) and 5-mode corrected PSF in the J and K band. The Strehl equivalent seeing for each degree of correction is given.

profiles in fig. 4. The diffraction limited core becomes a dominant feature, even in the J-band, simply by applying tip/tilt correction. The PSF becomes strictly diffraction limited at K (Strehl ratio > 0.8) by 5-mode correction. Applying adaptive optics at these wavelengths is clearly a very appealing option. One important implication of using adaptive optics in the near IR is, that we will have to obey the Nyquist criterion for the telescope. This formally imply a pixel scale of 0.″05, which gives a FOV of 50″ with a 1024 x 1024 array.
We find that the key issue is weather or not we are pursuing adaptive optics for a near IR instrument, and if so, is it feasible to construct a *HiRAC* like module for this application? *HiRAC* do not transmit light beyond 1.2μ, but we have identified materials, which transmits essentially 100% out to 2.5μ. The critical issue is emmisivity, which must be studied in detail.
If we have to conclude, that it is not possible to apply the same technology for the near IR, as have been used for *HiRAC*,we are forced to consider other solutions. We believe that these issues should be cleared out as soon as possible.

7 Conclusion

When working in the diffraction limit, a different scaling law apply for the limiting magnitude. The solid angle subtended by a point source is inversely proportional to the area of the aperture. This implies, that the absolute sky flux recorded over the sky area covered by a point source is independent of the diameter of the telescope. For a fixed S/N and flux, we then get the following relation between integration time and telescope diameter.

$$S/N \propto \frac{flux \times D^2 \times \tau}{sky \times \sqrt{\tau}} \Rightarrow \tau \propto D^{-4} \qquad (1)$$

The conclusion seems to be clear; If you are diffraction limited, your telescope is too small, or your wavelength is too long. Having a look at the estimated image quality for 5-mode correction, we find that an optimum image quality is obtained around the I and J bands. At K, we are clearly at the limit. With it's proposed instrumentation, the Galileo telescope is likely to be four

times faster at K. On the other hand, in the I-band we expect an image quality around 0."20, while the ESO VLT is likely to deliver an image quality of 0."65. Since the S/N is proportional to the telescope diameter and inversely proportional to the image quality, we find the amazing result that applying 5-mode correction at the NOT will yield identical limiting magnitudes for the NOT and the ESO VLT unit telescope in the I-band.
Compared to existing instrumentation at the NOT, *HiRAC-II* is a fairly ambitious project. We do however believe that the effort and investment is worth while, given the overall quality of the telescope and site. *HiRAC-II* will enhance the imaging potential of the NOT to a level where very few telescopes are competitive, assuming we can also manage to improve the telescope itself. We find it important that the development of *HiRAC-II* goes on along with the continuous work on improving the image quality of the telescope, because the time scale for completion is likely to be similar.

References

[Andersen & Sørensen 96] Andersen, M. I. & Sørensen, A. N. : **Image quality at the Nordic Optical Telescope**, internal report, Nordic Optical Telescope, http://www.astro.ku.dk/m̃ia/hirac/