The High Resolution Adaptive Camera (HiRAC) for the Nordic Optical Telescope

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Abstract

The implementation and expected performance of a high resolution visible/near-infrared camera at the Nordic Optical Telescope (NOT) are discussed.

HiRAC is a simple adaptive optics system for the Nordic Optical Telescope on La Palma. It will correct for image motion (tip/tilt), and later also focus and astigmatism, thereby correcting 5 modes.

The best obtainable images with tip/tilt correction is estimated to be close to 0.2", and the diameter of the corrected field (the isoplanatic path) will be 3-4'. In this mode, the fast guiding system is capable of guiding on objects fainter than 18.th magnitude, implying a sky coverage above 80% .

With 5-mode correction, the best images is expected to be around 0.15", with typical values around 0.25. The sky coverage is reduced to 10-20% in this mode.

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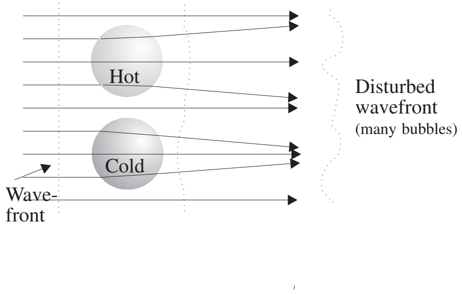

Figure 1: Tiny "bubbles" of hot or cold air induces refractive index fluctuations and thereby phase distortions of the wavefront.

1 Introduction

1.1 The turbulent atmosphere

When the light from an astronomical object transverse the atmosphere it is disturbed by tiny "bubbles" of hot or cold air. These "bubbles" causes locally changes in the refractive indexes of the atmosphere and thereby induces refractive index fluctuations. Due to these fluctuations the initially plane wavefront ,which is entering the atmosphere, will undergo large phase distortions (figure 1). The size over which the turbulence can be considered constant[5] is r_0 also called the Fried parameter.

The result of a turbulent atmosphere is that the image of a perfect point source no longer is a diffraction limited image (figure 2), but rather a large blurred image (figure 3).

1.2 The Adaptive Optics system

By measuring the local distortion of the wavefront over the entire entrance pupil, one can reconstruct the wavefront partially. The reconstruction is done by applying an aberration equal to the distortion, measured by the wavefront sensor, with opposite sign and thereby having diffraction limited imaging as a result. This reconstruction process is the principle of an Adaptive Optics (AO) system.

[5] The distortion is less than $\frac{1}{6}$ of the wavelength of the light

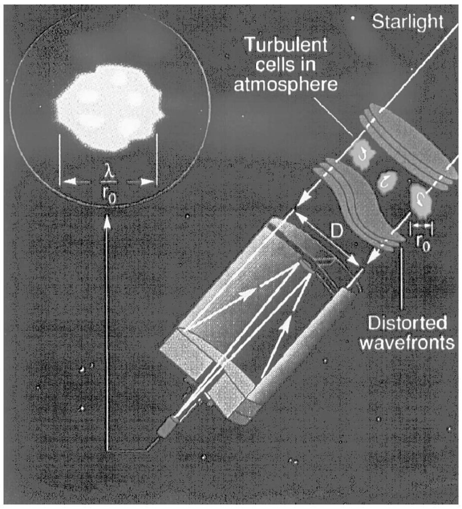

Figure 2: Without a turbulent atmosphere the image of a point source is diffraction limited.

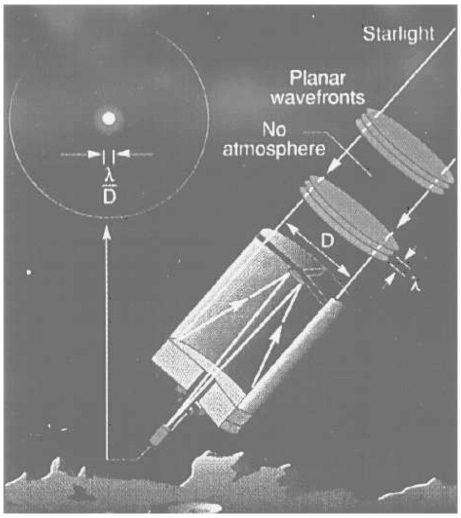

Figure 3: The turbulent atmosphere causes a blurred image.

2 Expected performance

Estimating the performance of an AO system can be done by the use of a computer model. The model is based on Kolmogorov's theory for the energy distribution of fully developed turbulence. It is extended by [Tatarski, 1961] and later [Noll, 1976] to a statistical model of the phase variations of a wavefront passing through the atmosphere.

2.1 Zernike Polynomials

The phase function is expressed as a modal expansion in terms of a set of basis functions $Z_j(r)$, which are orthonormal over the telescope pupil of radius R.

$$\Phi(r,\theta) = \sum_j a_j Z_j(\rho,\theta) \tag{1}$$

where $\rho = \frac{r}{R}$.
In general the zernike polynomials can be written:

$$\begin{aligned} Z_{evenj} &= \sqrt{n+1} R_n^m(\rho)\sqrt{2}\cos m\theta, m \neq 0. \\ Z_{unevenj} &= \sqrt{n+1} R_n^m(\rho)\sqrt{2}\sin m\theta, m \neq 0. \\ Z_j &= \sqrt{n+1} R_n^0(\rho), m = 0. \end{aligned} \tag{2}$$

where

$$R_n^m(\rho) = \sum_{s=0}^{(n-m)/2} \frac{(-1)^2(n-s)!}{s![(n+m)/2-s]![(n-m)/2-s]!}\rho^{n-2s}$$

The low-order zernike terms we are interested in are:

$$Z_{2,tip} = 2\rho\cos\theta \tag{3}$$

$$Z_{3,tilt} = 2\rho\sin\theta \tag{4}$$

$$Z_{4,defocus} = \sqrt{3}(2\rho^2 - 1) \tag{5}$$

$$Z_{5,astigmatism} = \sqrt{6}\rho^2\sin 2\theta \tag{6}$$

$$Z_{6,astigmatism} = \sqrt{6}\rho^2\cos 2\theta \tag{7}$$

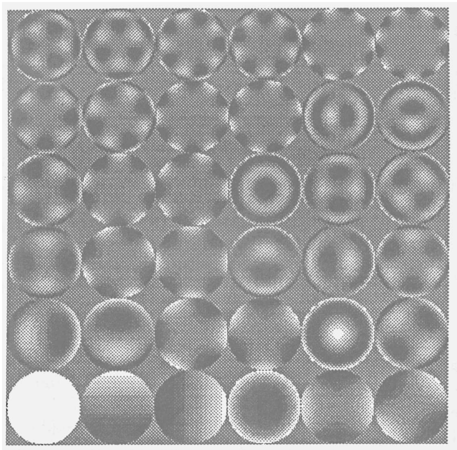

Figure 4: The 36 lowest zernike polynomials. Starting from the lower left the 2nd and 3rd display is tip and tilt. The following are defocus and two astigmatic terms .

Figure 4 gives a graphical display of the 36 lowest polynomials.

2.2 Perfect partial correction

If we make the (unrealistic) assumptions that the first N phase expansion coefficients can be determined to arbitrary precision by the wavefront sensor, and are perfectly compensated by the AO system, the corrected wavefront is:

$$\Phi(r,\theta) = \sum_{N+1} a_j Z_j(\rho,\theta) \tag{8}$$

The calculation of the amplitudes is not easy due to the fact that the amplitudes of the zernike polynomials are not statistically independent. Details can be found in articles by [Roddier, 1990] or [Wilson, 1995].

The point spread function (PSF) can be calculated from the knowledge of the wavefront $\Phi(r,\theta) = \Phi(x,y)$ and the pupil function $p(x,y)$:

$$psf(x,y) = |FT^{-1}[p(x,y)\exp i\Phi(x,y)]|^2 \tag{9}$$

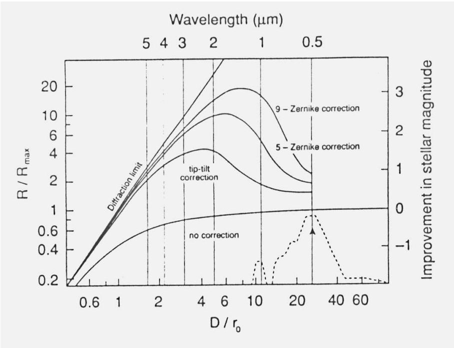

Figure 5: The normalized Strehl ratio (normalized to unity for an infinitely large uncompensated telescope) $\frac{R}{R_{max}}$ as a function of $\frac{D}{r_0}$ and radial order n. The working range of NOT is $6 < \frac{D}{r_0} < 25$. The upper scale indicates the wavelength dependence of $\frac{D}{r_0}$ but set for D=3.6m (CFHT) at $r_0 = 14.4cm$. Improved seeing conditions move the wavelength scale to the left.

A commonly used measure of image quality is the Strehl ratio. The Strehl ratio, R, is the ratio of the central intensity of the PSF to that for the unaberrated (diffraction limited) pupil. It gives a relative measure of the energy contained in the image core.

From figure 5 [Roddier, 1991] it is clear that there is an improvement in image quality by 2-mode correction (tip/tilt) and an even larger improvement by 5-mode correction.

To get a better view of the improvements of the image quality by the use of low-order adaptive optics under different conditions, the expected Strehl equivalent seeing[6] distribution at the NOT[7] has been plotted in figure 6. The telescope will with tip/tilt correction often work around 0.25" in the I-band and frequently below 0.3" in the V-band. With 5-mode correction it is possible to obtain a seeing angle of 0.15".

2.3 Sky coverage

The isoplanatic path[8] for image motion is ([Beckers, 1990]):

$$\theta_{image} = 0.314 \frac{D}{H} \tag{10}$$

where H is the average distance of the seeing layer. For NOT the isoplanatic path is:

$$\theta_{image} = 0.314 \frac{2.56m}{3000m} = 58'' \tag{11}$$

where we assume that the average distance to the seeing layer is 3000m.

To apply wavefront correction at the field of interest, you need a guide star. This star has to be within the 'isoplanatic distance' from the observed object, otherwise the measured distortion of the guide star is not equal to that of the object observed. It can be show [Soerensen, 1995] that a guide star of 18th magnitude can be used for tip/tilt correction at the NOT. The probability of finding such a star within 1' at the NOT is estimated by [Jensen, 1993]. The result is that tip/tilt can be applied on 80% of the sky and 5-mode correction on 20%[9]

The tip/tilt correcting camera will be able to improve image quality over the entire field of the CCD ,3-4', but with some variation in the PSF over the field. The best obtainable images will be those with the observed object placed in the center of the isoplanatic path.

[6] The seeing is scaled as follows: $seeing_{corr} = seeing_{uncorr} * \sqrt{R_{uncorr}/R_{corr}}$ where R is the Strehl ratio. Thus, if the central intensity is increased by a factor of 4, the 'Strehl equivalent seeing' is reduced by a factor of 2.

[7] The continuous seeing distribution from ESO-VLT site evaluation has been adopted but scaled to the median seeing value 0.75" at NOT corresponding to the seeing distribution given in NOT news no. 4.

[8] The area over which the fasevariance approximately is the same. For tip/tilt the approach is to only measure the average tilt over the entire telescope pupil.

[9] The rather big drop in sky coverage for 5-mode correction has at least 2 reasons: 1) The isoplanatic path is reduced. 2) The time it takes a turbulent element to cross the subaperature is reduced (since the subaperture is smaller) meaning that the available integration time is reduced and therefore a brighter guide star has to be available.

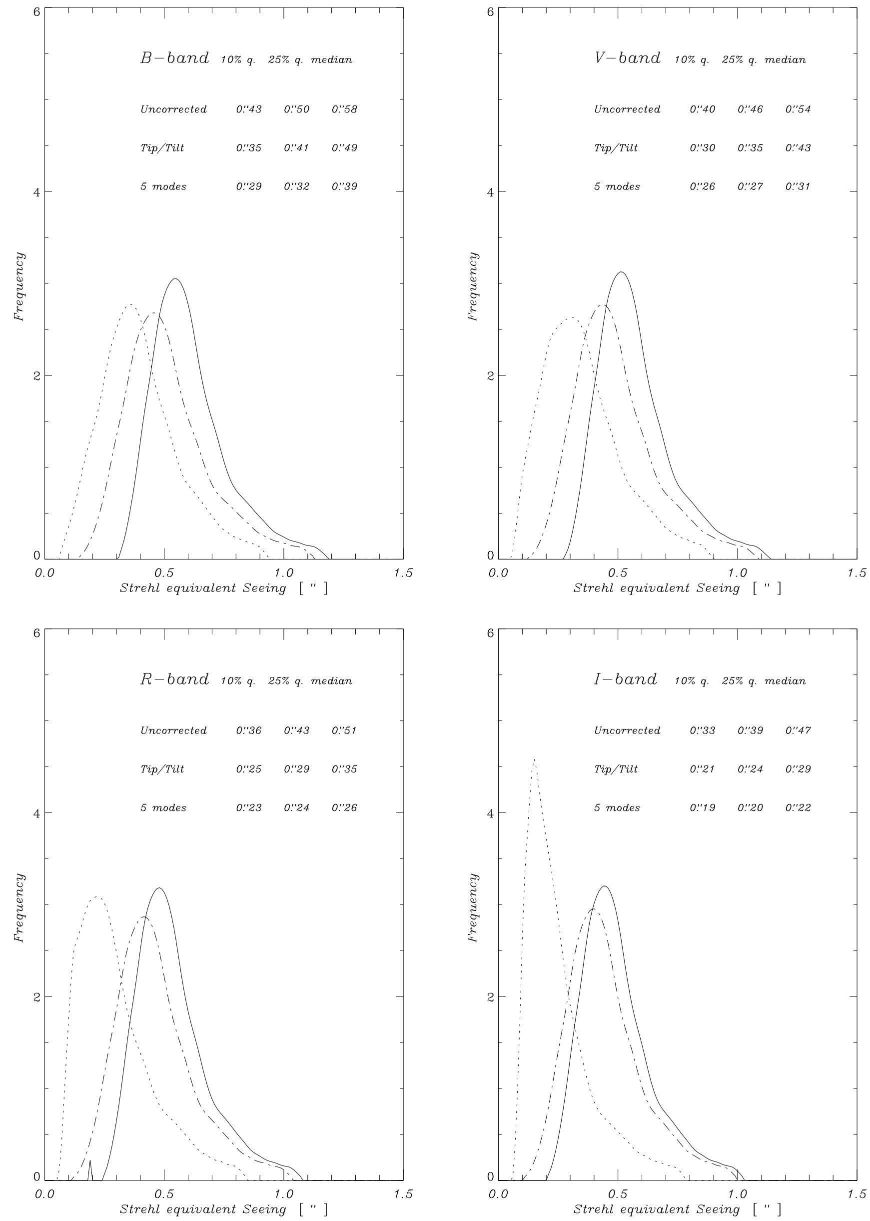

Figure 6: Strehl equivalent seeing distribution for low-order AO correction in B,V,R and I on the NOT. The tip/tilt correcting AO system is the dot-dashed curve and the 5-mode system is the dashed curve.

3 The Nordical Optical Telescope

In 1983 and 1984 agreement was reached in the four Nordic countries Denmark, Finland, Norway and Sweden concerning construction of a major observing facility for Nordic astronomers, the Nordic Optical Telescope (NOT). It was intended to cover observing needs in the Northern Hemisphere for astronomers from the four participating countries and be of high quality for both the optical and the infrared wavelength ranges. The telescope was to be erected in a place offering optimum conditions. Already before funding was decided, Nordic astronomers had agreed that the obvious choice for telescope site was at La Palma, Canary Islands.

The NOT was inaugurated in 1989. Located at 2382 meters above sea level, the NOT site is the highest of the observatory. The telescope has an altazimuth mounting, a fast, f/2.0, primary mirror of Ritchey-Chritie'n type, made of Zerodur, with a diameter of 2.56 meters. The effective f ratio of the telescope is 11.0 and the unvignetted field of view 25 arc minutes. The weight of the primary mirror is only 1925 kg and it is of a new generation of low weight mirrors necessitating a sophisticated support system in order not to deform significantly. The solution chosen is a circular mirror cell with a box section and a pneumatic support system.

An integrated servo system under complete computer control manages:

- rotation of the telescope with respect to azimuth and altitude axes
- rotation of instrument adapter
- pneumatic support system for the primary mirror
- focusing movements and lateral displacements plus tilting (if necessary) of secondary mirror
- auto-guider corrections
- rotation of building and data handling for implementation of refraction correction
- handling of data on temperature, pressure and relative humidity of ambient air plus continuous calculation and implementation of refraction data

4 Implementation of HiRAC

The High Resolution Adaptive Camera is a system which can correct for atmospheric image motion (tip/tilt) and later updated to correct defocus and astigmatism. HiRAC is intended to benefit the astronomers and not to impress the engineers. It may be technically possible (and technically interesting) to make high order correction but perhaps not very interesting for astronomically purposes.

The system is basically a smart front end to the standby CCD camera in the Cassegrain adaptor. A new filter and shutter unit has been made for the Brorfelde CCD camera, such that the instrument can be tested at the cassegrain focus. The individual parts of HiRAC are easily mounted because the unit is made more or less like an optical bench. The individual parts of HiRAC are:

- the tip/tilt corrector
- the guide probe
- the guide camera
- the guide CCD

The system can be described by following the light from the telescope (figure 7). The light first encounters the tip/tilt corrector then it passes through the guide probe, no light is reflected by the pickup mirror since the reflecting surface is on the other side of the mirror. When passing through the interference filter most of the light is reflected. The light transmitted is used for the science camera. The light reflected by the filter is directed towards the guide probe and focused on the surface of the pickup mirror (since the distance between the filter and pickup mirror is the same as the distance between the filter and science camera). When reflected by the pickup mirror the light passes through the guide camera and it is

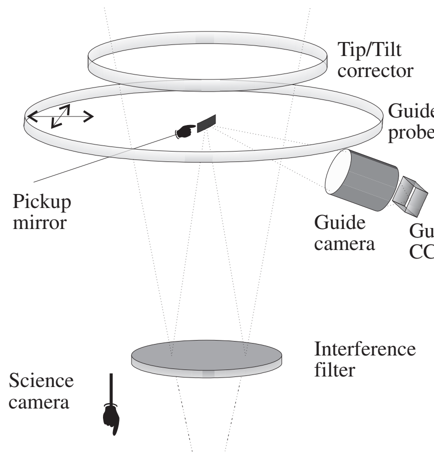

Figure 7: HiRAC

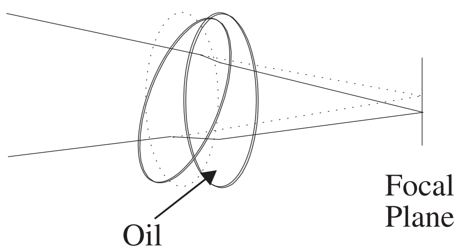

Figure 8: The principle of the tip/tilt corrector

then finially detected by the guide detector. Analysis of the detected signal gives information about the distortion[10] of the wavefront and the tip/tilt corrector can be adjusted and the loop is closed.

4.1 The tip/tilt corrector

The tip/tilt corrector is unconventional, since it is a variable wedge (a small angle prism). It consists of 2 plane parallel glass plates with a thin layer of oil in between (figure 8). The wedge angle is controlled by tip/tilting one of the plates with piezo electric actuators. The corrector works well up to 100 Hz, well beyond the expected requirement of 25 Hz.

[10] In the case of tip/tilt correction only image motion is detected

4.2 The guide probe

The guide probe can be shifted in two directions making it possible to place the very small pickup mirror (0.5 x 0.5 mm) exactly at the image of a guide star.

4.3 The guide camera

This is a simple adjustable two lens system making it possible to image the guide star on the guide detector.

4.4 The guide detector

The detector for the guide probe is a LORAL 64x64 pixel CCD with a low readout noise (RON). The RON measured[11] was 3.5 e^-.

Since the 64x64 CCD can be read at very high frame rate it's ideal as a guide detector. Reading only a sub-frame of the CCD, the camera can be read at a frame rate of 400 Hz well beyond the expected readout frequency of 25 Hz. This is very useful when optimizing the servo loop and when used for 5-mode correction.

Image motion detection is done by using the detector as a quadrant detector reading only 2 by 2 pixels at a suitable binning. The noise contribution from RON is thereby minimized. At a RON less than $5e^-$ the CCD[12] performs as well as Avalanche Photo Diodes[13] (APD's).

4.5 HiRAC in the future

As already mentioned earlier HiRAC is later upgraded to a 5-mode correcting system. The upgrade is being developed by M. I. Andersen and P. C. Damm. Prototype testing is already in progress.

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[11] tested by Craig MacKay (Cambridge, UK)

[12] CCD's are prefered because the opto-mechanical coupling is easier and it can also be used when more than 2 modes are corrected

[13] APD's are photon counting devices and therefore essentially noise free

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