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Astronomical Instrument Centre

Report #1: Commissioning of HiRAC at the Nordic Optical Telescope, January 8-16, 1996

by

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1 Introduction

The aim of this report is to document the performance of *HiRAC*, based on the tests done during the commissioning period. We had eight nights, which we shared with the staff. The first three nights were used to upgrade the top unit by the staff and install new fibers in the cable twist. Meanwhile, we aligned the optics of *HiRAC*, tested the software and hardware 'on the ground' using our artificial guide star. *HiRAC* was mounted on the telescope on the 11th. Observations were terminated on the 14th, due to bad weather (half a meter of snow). During the three nights we could observe, seeing was unfortunately rather bad and unstable, ranging from 0″.6 to 1″.8.
The science detector for *HiRAC* is BroCamII, a 2K Loral CCD, thinned by Mike Lesser. It has a QE above 65% from 3000 to 8000 Å and a peak QE of 93% around 5500Å.

2 Performance of the Tip-Tilt system

There are two ways, in which we can test the performance of the Tip-Tilt system in *HiRAC*. The obvious way is to compare images where T/T correction have been applied with images without T/T correction. However, this approach does not give much information about the characteristics of the system.
A more elaborate way to test the Tip-Tilt servo loop is to read the science camera with an open shutter, while running the T/T servo loop. In this way, we obtain one (or more) star trails. From a trail, we then can derive the 1D image motion. By this approach, we do not get the same information about the system behavior along the direction of the star trail. The more uniform intensity of the trail does however show, that image motion along the trail is compensated.

Figure 1: Star trails recorded by reading out 43 lines per second. Upper trail made using auto guiding only. Lower trail made with HiRAC guiding at 50 Hz, using the same star as signal for the quadrant detector.

2.1 Star trails

The science CCD is read at a rate of 73 lines/sec for the data to be discussed in this section. The sampling is 0″.22 (2x1 binning) and the seeing was typically around 0″.8 - 1″.2 . The smearing introduced by the seeing works as a low pass filter, with a cut off frequency around 8Hz. These star trails were therefore not able to properly sample the dominant telescope oscillations at 11Hz and 16Hz. Later in the run, we were able to increase the sampling speed to 444 lines/sec, thereby allowing us to investigate telescope oscillations.
In fig. 1 we show images of star trails, taken without and with T/T correction activated. The correction for image motion is directly visible from the image. A more detailed analysis of these

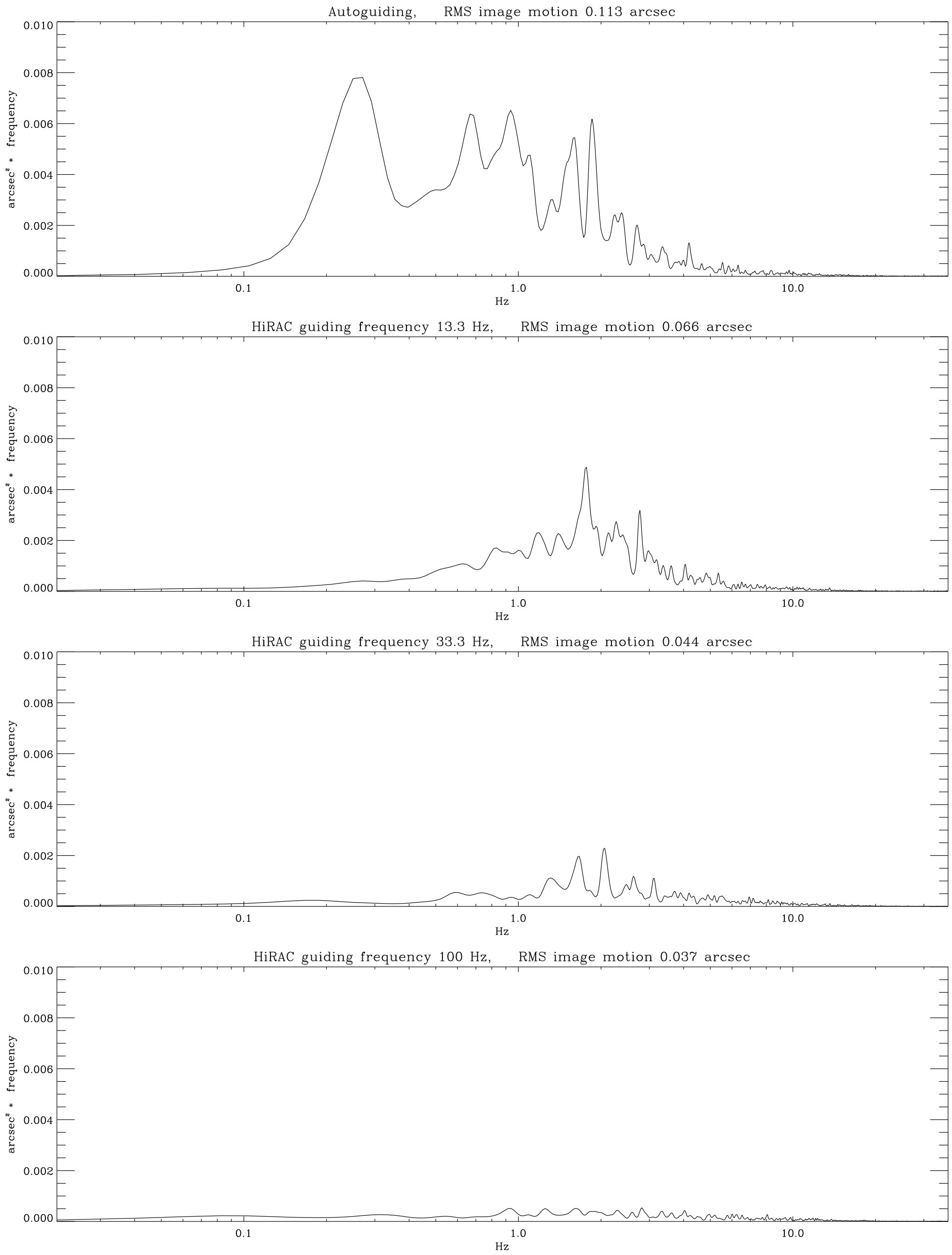

Figure 2: Frequency analysis of image motion for different guiding frequencies. Upper plot shows motion from 0.2 Hz to 5 Hz while auto guiding. Guiding with HiRAC strongly reduces image motion with frequencies below one tenth of the guiding frequency.

data is best done, computing the power spectral density. We show typical power spectra in fig. 2. Most of the image motion is removed when guiding at 13Hz. When guiding at 50Hz, virtually no image motion is left, partly because the seeing is filtering out high frequency image motion. In fig. 3, an uncorrected power spectrum, a corrected power spectrum and the ratio of corrected to uncorrected power spectrum is shown. The ratio between the power spectra is basically the transfer function of the system, if we ignore that the raw input power spectra are

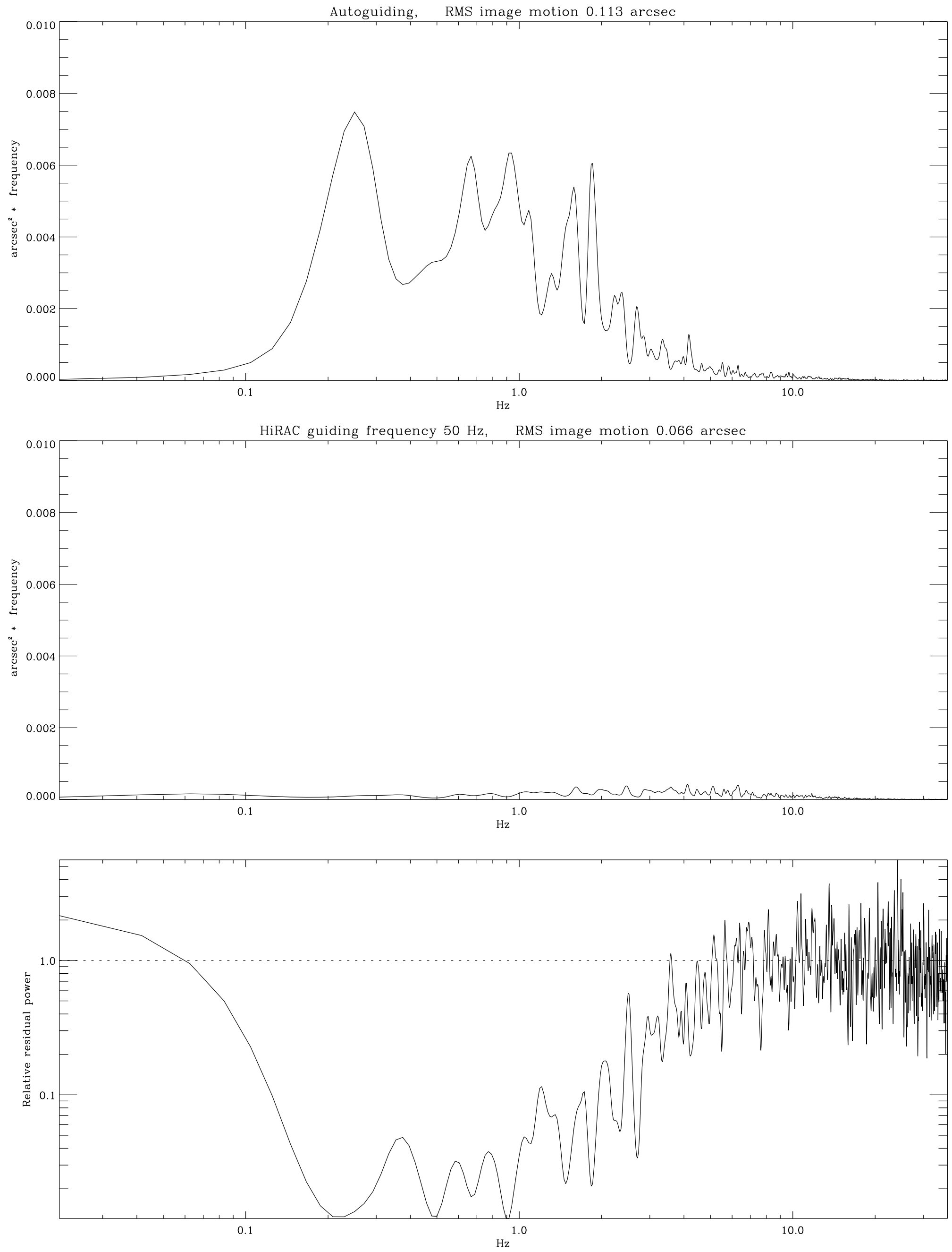

Figure 3: Upper plot: Power spectrum of image motion during auto guiding. Middle plot: Image motion reduced by guiding at 50 Hz. Lower plot: Ratio of image motion in the two situations. At about one tenth of the guiding frequency, HiRAC is no longer able to stabilize image motion. Above this frequency, guiding errors increase the motion, which is not detected here because of the low star trail sampling frequency.

not identical[1]. The transfer function is below unity for frequencies below $\approx$0.1 times the guiding frequency. This is in close agreement with our detailed simulations, where we used time series

[1]We are not able to record corrected and uncorrected image motion simultaneously. Therefore the statistical fluctuations of the atmosphere is introducing noise in the derived transfer function

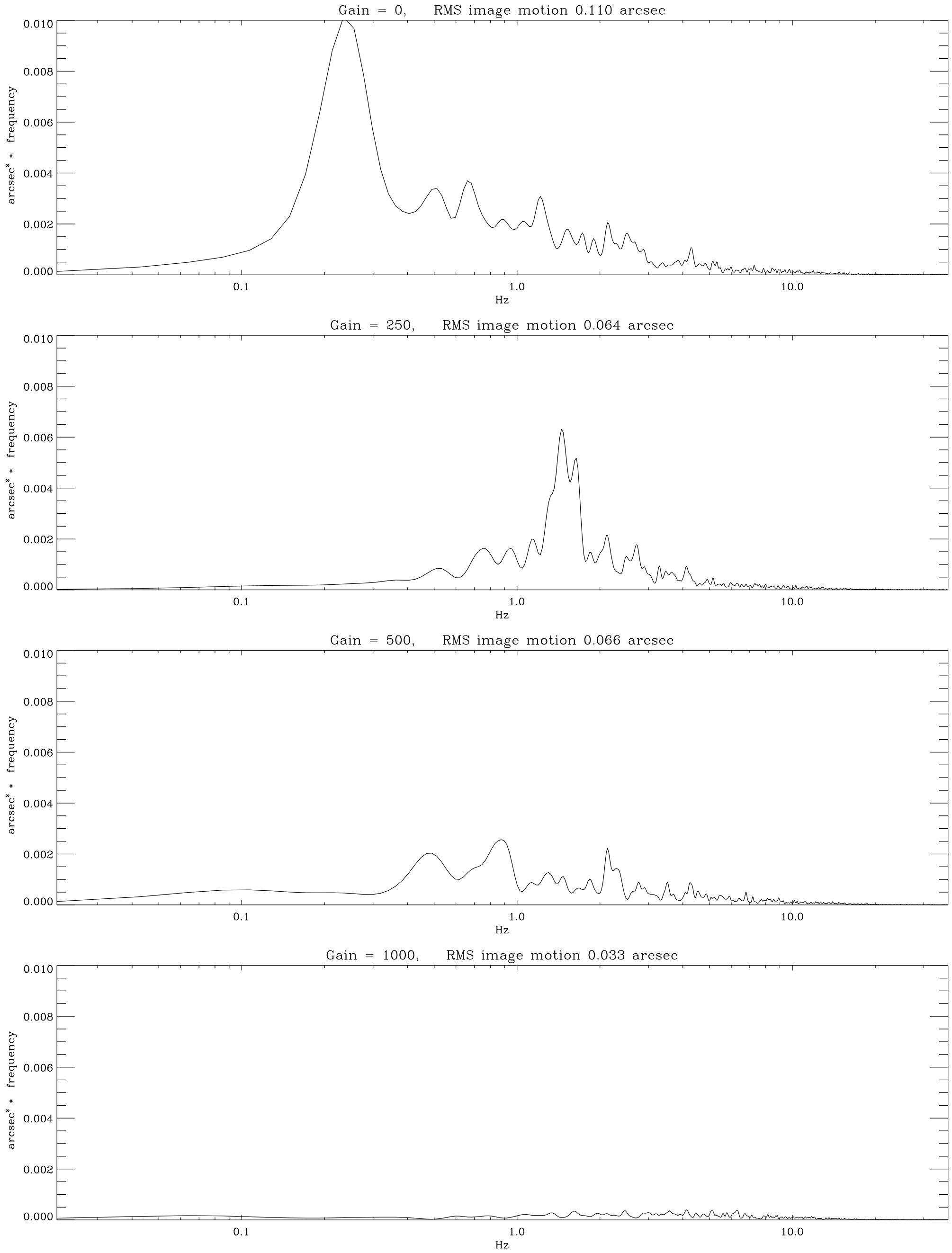

Figure 4: Correction for various values of the gain factor in the servo loop. Gain = 0 is equivalent to auto guiding only. As gain increases, the correction improves, until at a gain larger than shown here, over correction introduces oscillations. The optimum gain is a function of seeing. Normally the gain is determined automatically by the guide camera. In the present case the auto-gain routine preferred a value of 1200.

images taken at the NOT in October 94, as well as data from our artificial star, as input. The low frequency part of the image motion is removed very effectively, although not fully matching the (mathematical) simulations. At frequencies above 0.1 times the guiding frequency, image motion is amplified (transfer function above unity), although not as much as our simulations show. The characteristics of the servo loop is dependent upon the servo loop gain, as shown in fig. 4.

2.2 FWHM from images with and without T/T correction

On two nights, series of images were taken, every second image being T/T corrected. As can be seen from fig. 5, these were by no means convincing. There are small improvements to be observed, but the fluctuations of the seeing from one exposure to the next are of the same order of magnitude. The main reason for the smaller than expected improvement in image quality is a much less dominant image motion.

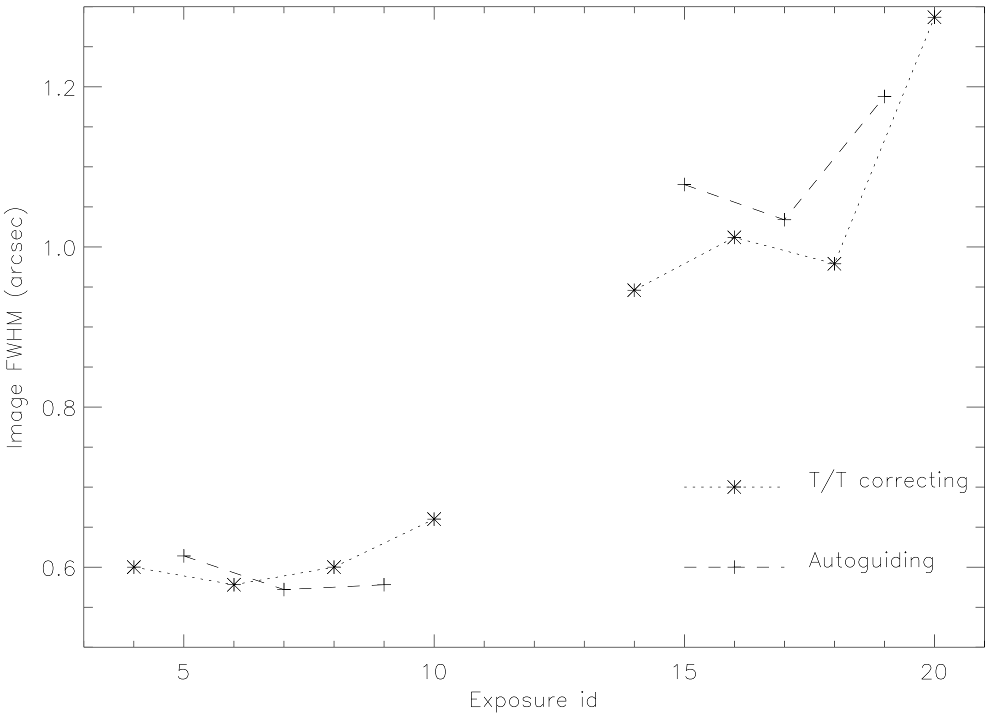

Figure 5: FWHM of one minute exposures. Leftmost set: January 13, using I-band filter. Rightmost: January 12, using V filter. The guiding frequency was 50 Hz. Very bad seeing during exposure #20 caused HiRAC to temporarily loose the guide star.

3 Expected improvement of image quality

When we started out on the project, we based calculations on the simple assumption that the turbulence was described by the Kolmogorov spectrum with an infinite outer scale length[2]. From this assumption the statistical distribution of Zernike aberration terms can be calculated, and accordingly the performance of a given adaptive optics system evaluated.
It is now becoming clear, that the outer scale length is not infinite. Jean Vernin has been measuring turbulence from the NOT twice, and guesses the outer scale length to be of the order of 2.5m, implying that not much structure above the size of the telescope pupil is present. This matches well the observations at the Keck telescope, where essentially no image motion is seen.

[2]The outer scale length is basically a measure of the largest turbulent structure in the atmosphere.

We have typically measured image motions of 40-60% of that predicted by the Kolmogorov spectrum with infinite outer scale. According to calculations by [Voitsekhovich, V. 95] on the amplitude of Zernike terms depending on the outher scale length, L_0, we estimate an outer scale length of 5 – 8 meters during the observations listed in table 1. In this range, the coma term of turbulence is practically not attenuated. As coma is partly interpreted as image displacement by our quadrant sensor, this will further reduce the expected gain in image quality from tip/tilt correction.

In table 1 image motion measurements from trails during a number of observing runs is given[3]. We also give the measured long time FWHM, the average FWHM measured from the individual lines along the trail, and estimate the T/T corrected seeing from the relation

$$FWHM_{corr}^{5/3} = FWHM_{raw}^{5/3} - FWHM_{image\ motion}^{5/3} \tag{1}$$

where

$$FWHM_{image\ motion} = 2.35 \times \sigma_{image\ motion} \tag{2}$$

Table 1: FWHM, image motion and expected T-T corrected FWHM.

FWHM$_{raw}$	FWHM$_{image\ motion}$	FWHM$_{corr}$	FWHM$_{trail}$	Comment
1.10	0.17	1.07	1.00	Mar 19, 1994
2.13	0.45	2.03	2.08	Mar 20, 1994
2.60	0.75	2.40	2.50	Mar 20, 1994
0.46	0.21	0.38	0.39	Okt 17, 1994
1.21	0.54	1.01	0.98	Jan 12, 1996 auto guided
1.69	0.59	1.50	1.53	Jan 12, 1996 auto guided

The estimated FWHM and the FWHM of the trail match quite well, but with some scatter to each side. We find that the FWHM will improve by ≈0.″1, almost independently of the seeing. In reality we will only be able to achieve an improvement of ≈0.″08, due to residual image motion. This is a factor of two less than what was hoped at the beginning of the project.

4 Measurement of isoplanatic patch

Observations of star trails in an open cluster give us the possibility to measure the isoplanatic patch for image motion. The isoplanatic patch is the size of the area within which the correlation of motion is larger than 0.5. Inside this patch, the image quality will improve, and outside it will degrade. We show two sets of star trail images in fig. 6, one being T/T corrected. With the BroCam controller system, we are able to redefine the CCD to have a virtual size, and thereby

[3]The October 94 data are from time series imaging

increasing the number of lines being read. The images shown here are 1024x5000 pixels. The reduced star trails are shown in fig. 7 and fig. 8.

The correlation can now be calculated for pairs of star trails. We do this only for the non corrected image, since the correlation has little meaning for the corrected trails. By plotting the derived correlations as function of separation between the stars, the size of the isoplanatic patch can be estimated. However, fig. 9 reveals, that it is far larger than the size of our field of view. The correlation is above 0.95 for any pair of stars in the field.

From this, we would estimate an isoplanatic patch of at least $20'$, which, if caused only by the atmosphere, implies that most of the turbulence is located at an altitude of less than 150 meters. The patch is much larger than expected, which may be explained by telescope motion being the source of a significant part of the stellar motion observed. The isoplanatic angle for guiding errors is infinite (tracking errors are the same all over the sky). Nevertheless, the isoplanatic patch we estimate is the one relevant for observations, since it refers to actual conditions at the focal plane. Previously, one of us (ANS) has measured the isoplanatic patch to vary from $1\overset{'}{.}5$ to $4'$, using the NOT in "idle" mode, thus eliminating tracking/guiding errors.

We have too few measurements to say anything about the typical size of the isoplanatic patch. It is therefore important, that such measurements are continued on as many nights as possible.

Figure 6: Star trail images using the entire field of view of the CCD. The read out speed is 43 lines per second. 500 lines of the 5000 lines big image is shown here. Upper image is made using auto guiding. The similarity of the motion of individual stars is not readily apparent, due to the different positions of the stars along the trails. The lower image is with HiRAC guiding at 50 Hz. The brightest star is used for guiding. Note how the correction degrades with the distance to this star, but remains better than the image made during auto guiding over the entire field.

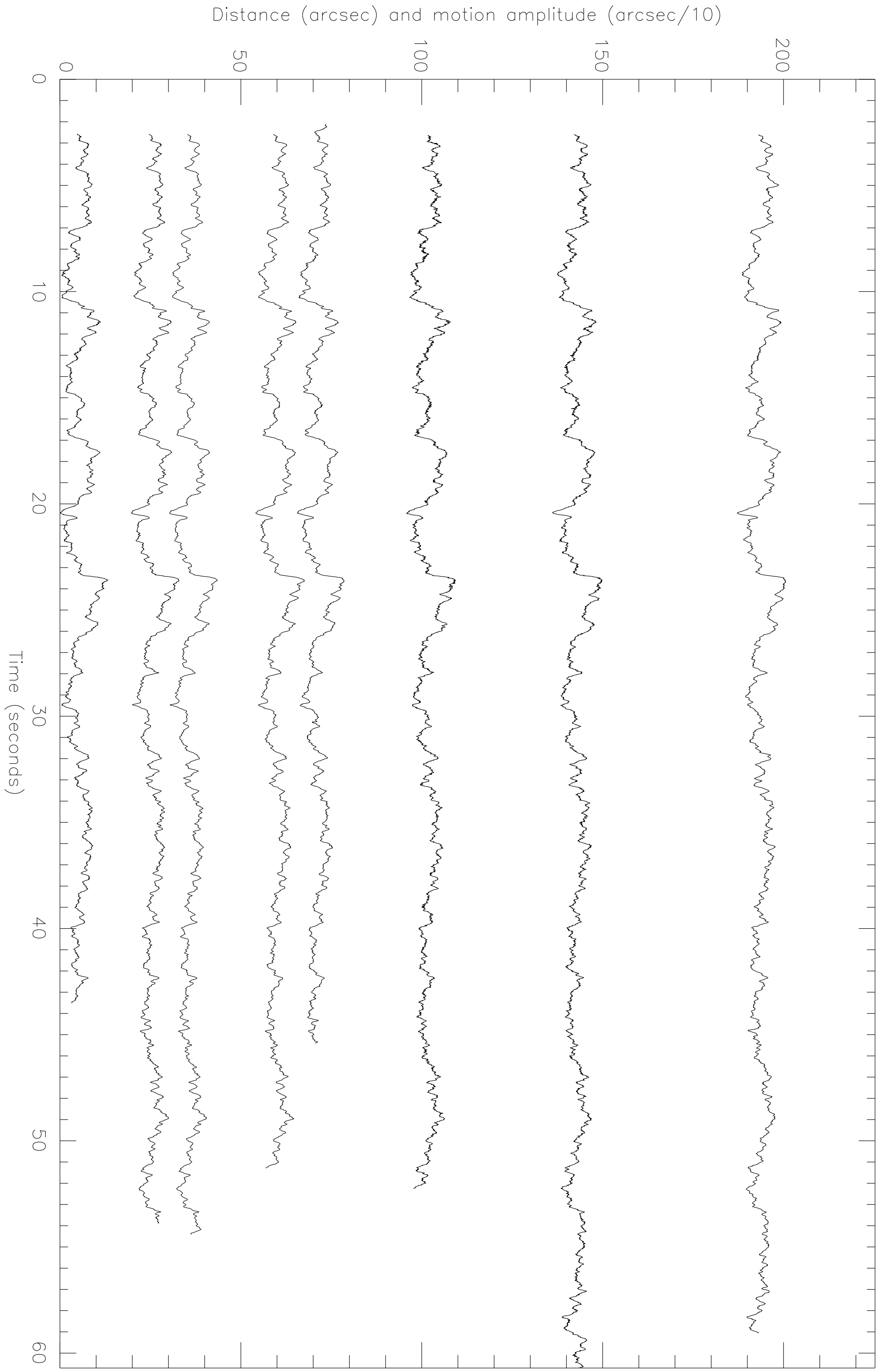

Figure 7: Positions of eight stars extracted from a star trail image made using auto guiding. The distance between the trails reflects the distance between the trails in the image. The image motion is magnified by a factor of 10. The similarity of motion over all of the field is readily apparent.

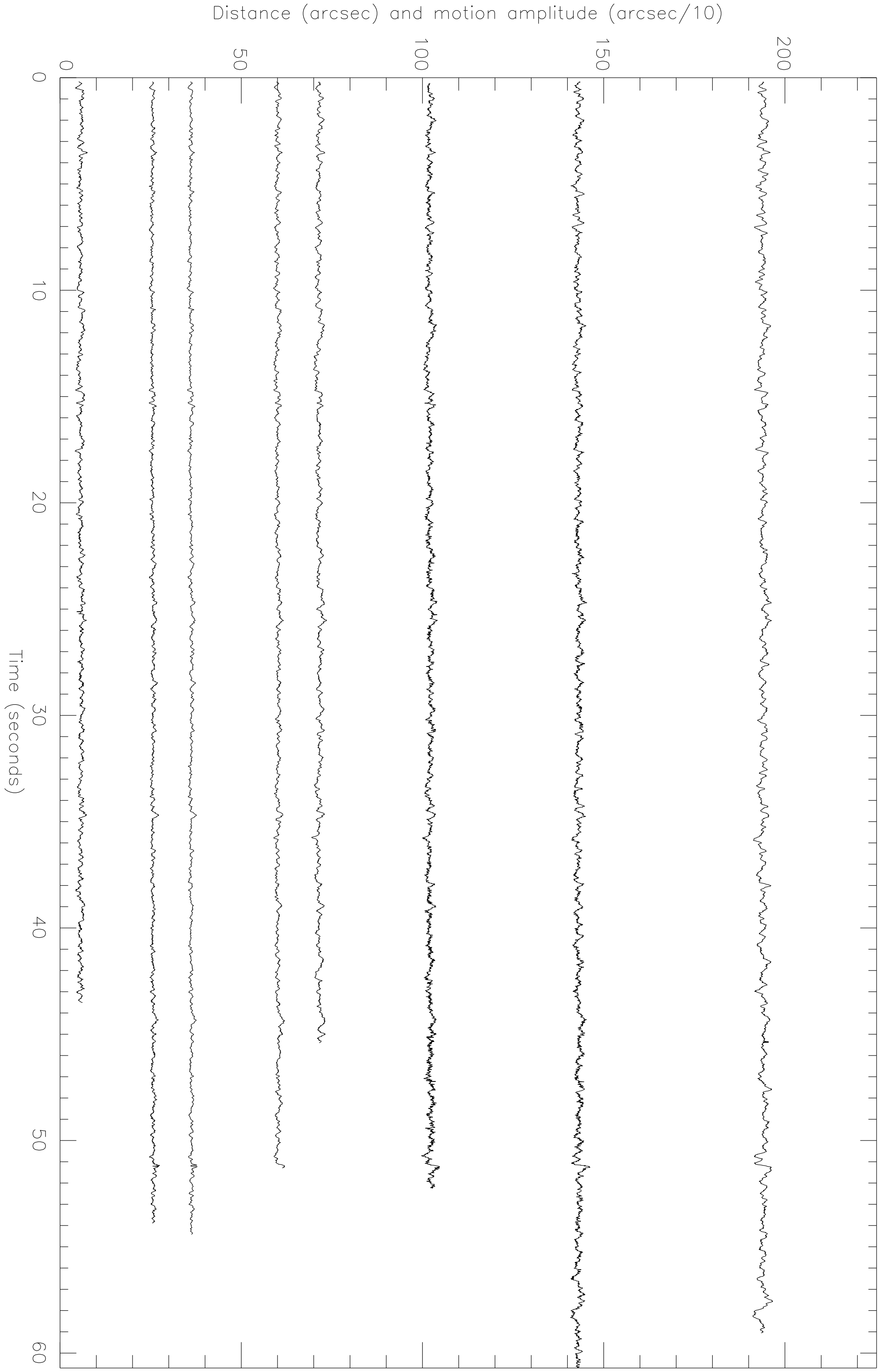

Figure 8: Positions of eight stars extracted from a star trail image made with HiRAC guiding at 50 Hz. The distance between the trails reflects the distance between the trails in the image. The image motion is magnified by a factor of 10. The third trail from the bottom is from the star used for guiding.

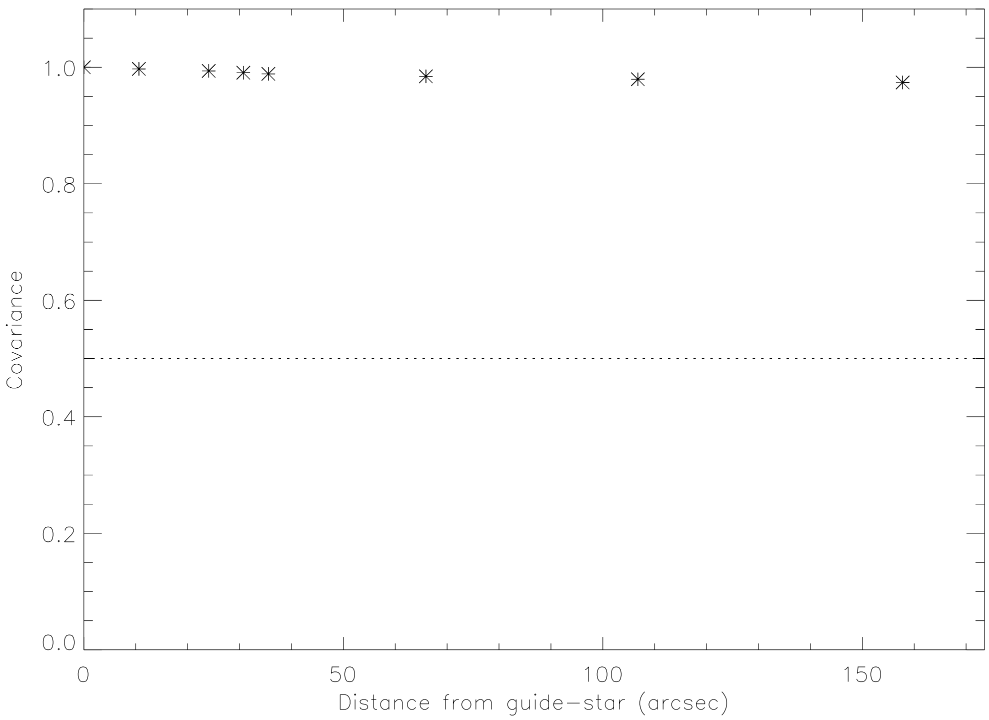

Figure 9: The correlation of image motion in pairs of trails, depending on the angular distance between the stars. A very high correlation is seen over the entire field, indicating an isoplanatic patch for image motion much larger than $3'$.

5 Telescope and T/T oscillations

On the 13.th of January, we used other software to control BroCamII, which allowed us to read a small strip of the CCD (100 pixels) at a speed of 444 lines/sec. This allowed us to investigate the behavior of the system up to frequencies of ≈100Hz. Again, we show uncorrected and corrected power spectra (fig. 10), and recognize the well known 11Hz and 16Hz oscillations. As expected, the T/T system will amplify these oscillations, when guiding at 67Hz. The wind speed during these observations were 12m/s, and it is therefore not surprising to see the oscillations.

The T/T unit is a rather unconventional optical device, consisting of two plane parallel glass plates, of which one can be tip-tilted by the aid of piezo electric elements. The space between the two glass plates is filled with an optical fluid, producing a variable angle prism, as we can move one of the glass plates.

At this point during the test, we had still not seen convincing evidence of a clear improvement of the image quality, and we had a nagging doubt that there were some 'hidden' problem in the T/T unit. We therefore decided to increase the guiding frequency to rather extreme values, because we could now sample star trails with much higher frequency than previously. Due to the bad weather, we were using the artificial star with turbulence generator. At the limiting guiding frequency of 200Hz, we were in fact able to induce an oscillation in the T/T unit. At this guiding frequency, the T/T unit sounds as if it could break at any given moment. From the power spectrum (fig. 11). we derive a frequency of approx. 30Hz for the oscillation. From 125Hz and up, the frequency is present in the power spectrum, but with much smaller amplitude. Most important, there is no sign of a broadening of the width of the star trail. This show that we do not introduce aberrations in the glass plates, even by this crude treatment of the T/T unit. We are therefore convinced, that the T/T unit is working as expected, as long as the guiding frequency is kept at 100Hz or below.

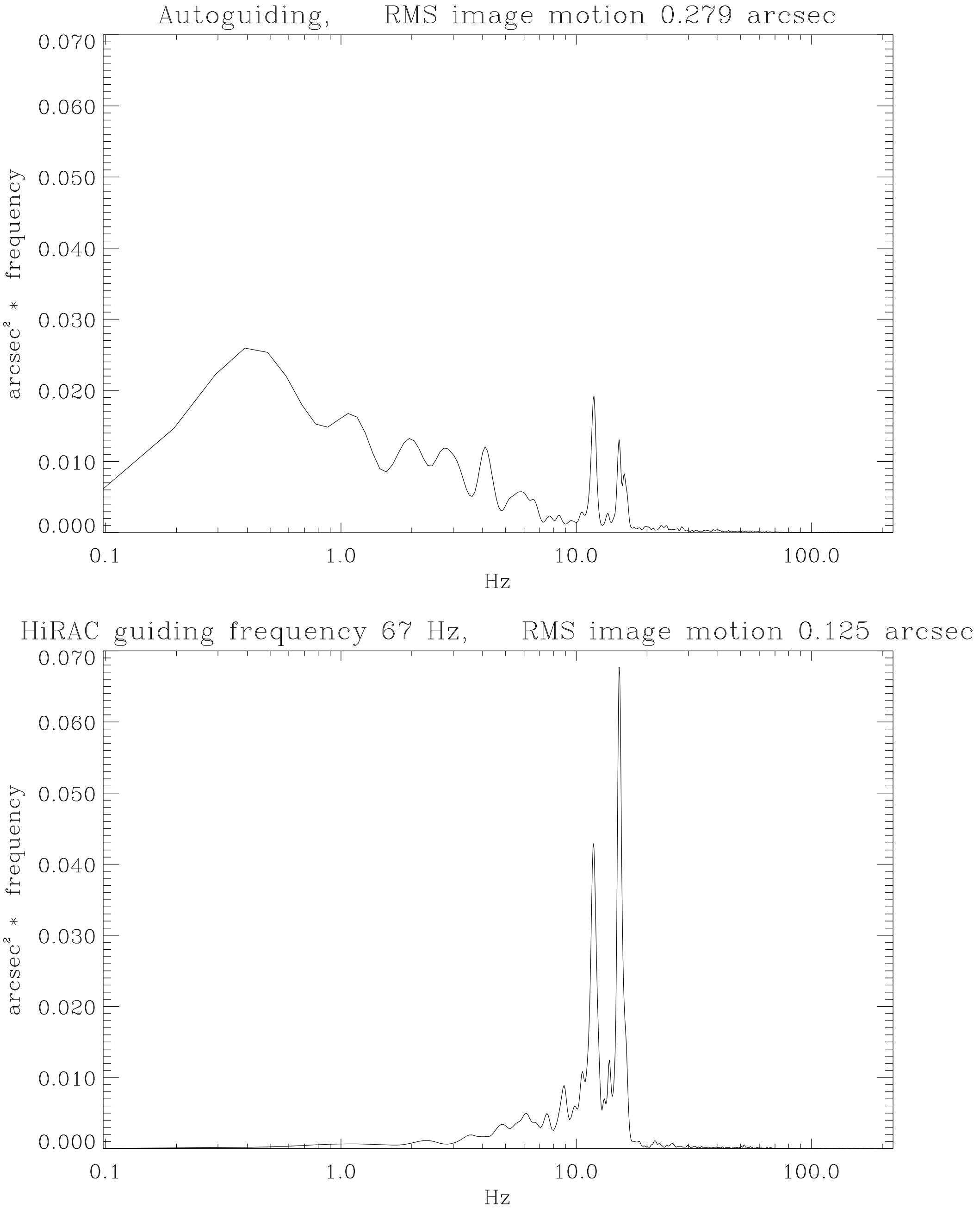

Figure 10: Image motion while auto guiding and while fast-guiding at 67 Hz. Telescope oscillations are present at 11Hz and 16Hz. As HiRAC amplifies image motion above one tenth of the guiding frequency, the oscillations are strengthened.

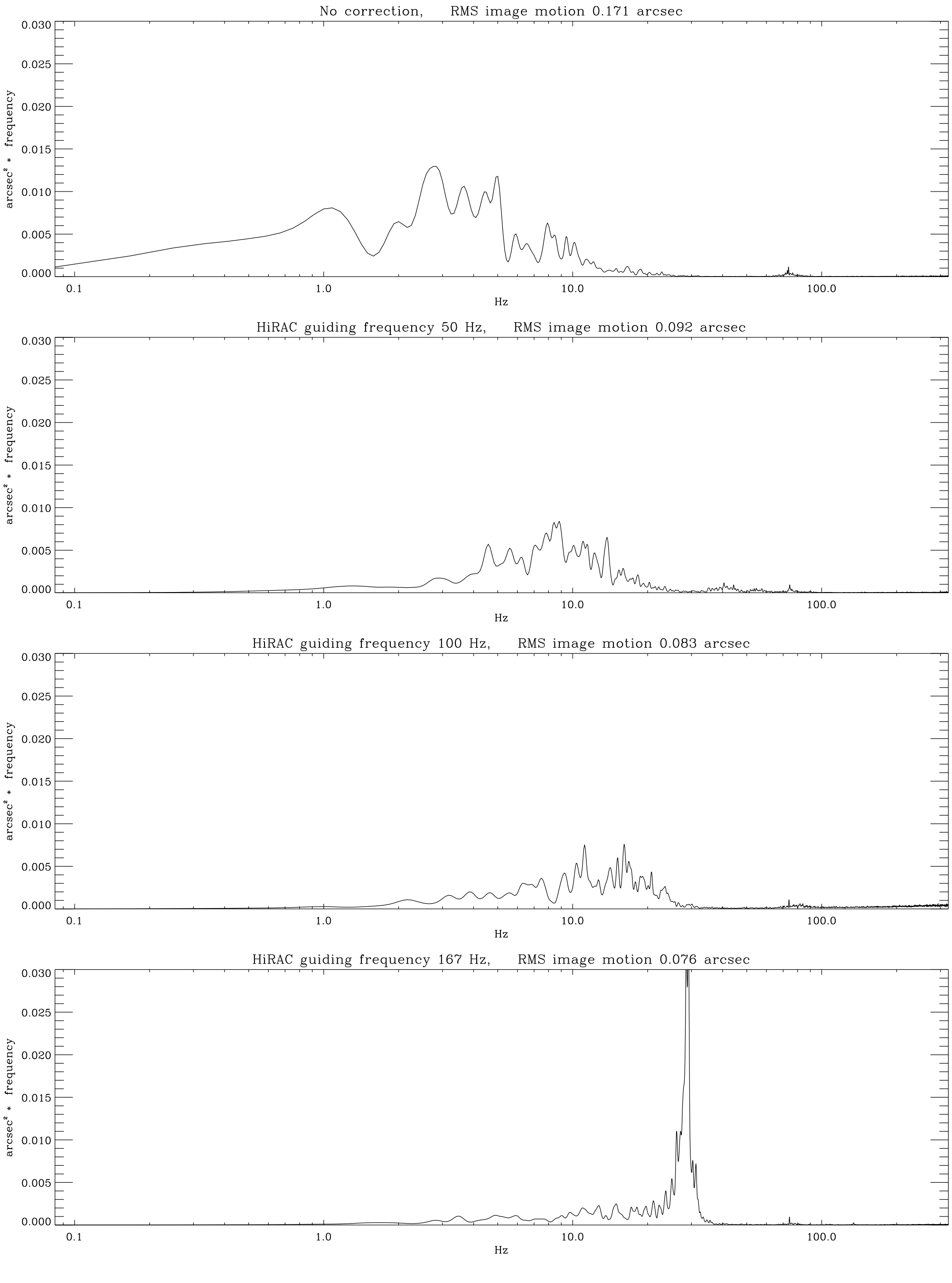

Figure 11: Power spectra from star trails made using the artificial star and turbulence generator. Image motion above 0.1 times the guiding frequency is seen to be amplified. As guiding frequency is increased above 100Hz, an oscillation is induced at around 30Hz. The oscillation at 75Hz is from the fan in the turbulence generator.

Table 2: Detected and expected flux in guide camera from a V=20 A0V star.

Filter	Expected flux $[e^-]$	Detected flux $[e^-]$
U	169	8
B	175	18
V	195	25
R	95	20
I	?	8

6 Limiting magnitudes

The guiding camera installed in *HiRAC* has a read out noise of 5e-, which we believe to be significantly above what can be achieved with the CCD. We hope to improve on this, when we have a possibility to install the spare camera.

We have measured the flux detected by the camera, for each of the special *HiRAC* filters. We used an A0V star for this. The detected and expected flux is given in table 2 [4]. There are very severe discrepancies between the expected and detected flux. We detect around ≈10% of the expected flux. The discrepancy is so large that we suspect an error made by us. We will contact the NOT staff for further investigation of this problem.

For guiding, ≈120 e^- per integration is needed. In the presence of telescope oscillations, the lowest reasonable guiding frequency is ≈13Hz. Accordingly, the limiting magnitude for the guiding system is around 15.5.

[4] We do not have information about the reflectivity of the I filter

7 Remaining software and hardware work

Some work remains to be done, before *HiRAC* is in a fully operational state. The most important problem is the sensitivity problem of the guide camera.
The software controlling *HiRAC* is basically an extension of the BIAS program controlling BroCamI. The CCD part of the program is therefore working quite well. We have to improve on the guide star acquisition. At the moment the observer must take a fast (binned) acquisition image with BroCamII. By pointing on a star, the T-T guide probe in *HiRAC* will be moved to the position corresponding to the star. The observer then has to take an image with the guide camera, to ensure a correct centering of the star (it must be within $0\farcs2$). We aim at an automatisation of this last step, whereby the time spent on guide star acquisition should be reduced to below one minute. Other issues to be taken care of are

- Technical manual, including an overview of available documentation.
- Engineering test software (test of T/T unit and guide camera).
- A proper users manual - to be written in collaboration with the staff.
- Optimized guide camera (read noise and bias stability).
- A mechanical cover at the T/T unit (there are some uncovered openings around this module).
- Auto focus, using the guide camera.
- TCS-interface.
- A user friendly implementation of star trail mode.

8 Conclusions

In short, we can conclude that the Tip-Tilt system is working, but we have a serious problem with the sensitivity of the guide camera. We will have to investigate this problem in the near future.
We have been fairly unlucky with the seeing, preventing us from showing convincing evidence, that images do in fact get sharper by T/T correction. The variability of the seeing was such, that image motion occasionally jumped by a factor of two while recording a star trail. Tests with our artificial star, have given reproducible results with a clearly improved image quality.
We do now have clear evidence, that the image motion above La Palma is smaller by $\approx$a factor of two, compared to what is predicted by simple Kolmogorov theory. We interpret this as an outer scale length of the turbulence of $\approx$8m. From the autocorrelation of star trails, we conclude that a significant fraction of the image motion is due to telescope motion, which we effectively correct.
The improvement achieved with T/T correction is very sensitive to the performance of the telescope. The severe telescope oscillations will occasionally prevent the system to deliver improved

images. Also, the lack of a working active optics system limits the performance of the telescope as a whole, and will severely diminish the improvements achieved through T/T correction. Meanwhile, we should be happy to have a telescope, which is still a top end imaging facility. For deep imaging, the NOT now compares quite favorably with telescope like the WHT and the ESO NTT.

References

[Voitsekhovich, V. 95] Voitsekhovich, V. V. and Cuevas, S.: **Adaptive optics and the outer scale of turbulence**, J. Opt. Soc. Am., Vol 12, No 11/November 1995/p. 2523 - 2532