CHIRON efficiency tests

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In this document, we report the tests that have been performed on CHIRON in order to understand its efficiency.

1 Fiber throughput and FRD measurement

We have injected a HeNe laser at 543 nm into the science fiber. A set of lenses and a diaphragm (in collimated space) were used after the laser to inject the beam with the correct focal ratio. The diameter of the diaphragm was set to 4 mm, while the focal length of the focusing lens was 19 mm, which gives an input focal ratio (IFR) of F/4.75.

After aligning the fiber in x, y and z directions, we measured the power after and before the fiber,

$$P_{\text{before}} = 935 \pm 10\mu W \text{ and } P_{\text{after}} = 835 \pm 10\mu W, \tag{1}$$

which gives a transmission of $89 \pm 2\%$.

In order to measure the focal ratio after the fiber, we have plugged the fiber into a connector and then recorded images of the far-field at different fiber positions (in the z-direction). For every image, we then fit a gaussian to the intensity distribution mashed in one direction (including speckles) and calculated the FWHM of that gaussian. Table 1 and Figure 1 (blue solid line) summarize the results. The blue dashed line in Figure 1 is a linear fit to the data. The slope of this line gives the output focal ratio (OFR). Given this definition, we find $\text{OFR}_{\text{FWHM}} = F/6.4$. In reality, this F/6.4 only encompasses 75% of the energy, so the beam is actually faster (depending on the definition).

Position (in mm)	FWHM of gaussian fit (in mm)
0.0	9.3
1.2	9.48
3.4	9.84
4.9	10.03
6.2	10.11
7.3	10.43
8.2	10.66
9.1	10.71

Table 1: FRD measurement for the fiber used on CHIRON when fed at F/5 by the laser

The current fiber is similar in throughput to the three other CHIRON fibers that we measured (the old spare fiber cable that was in the Coudé room and the two new fibers we brought during this trip. These fibers all had a transmission around 90%. The current fiber is also the one that performs the best in terms of focal ratio degradation (F/5.1, F/4.5 and F/4 for the other fibers keeping the same definition). It is therefore preferable to keep using this fiber on CHIRON.

2 FRD measurement while guiding on Alpha Cen A

We have repeated the FRD measurements of Section 1 but this time, we were not injecting laser light into the fiber but we were guiding on Alpha Cen A.

The results are summarized in Table 2 and Figure 1 (red solid line). Using this particular set of data and the OFR definition of Section 1, we find $\text{OFR}_{\text{FWHM}} = F/5$, which is considerably faster than when measured with the laser. If the laser beam was just filling the APO, we would have additional losses of 38% when guiding on a star because of this faster beam. Note that this number might not be representative of actual losses as the output focal ratio can change depending on the fiber illumination,

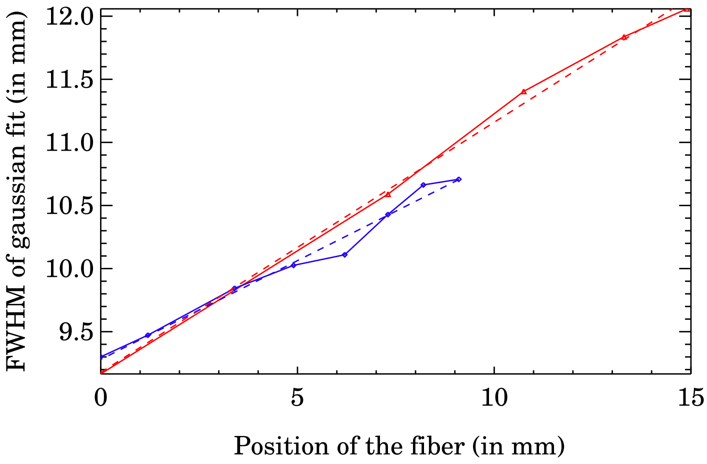

Figure 1: Output focal ratio of the science fiber when fed at with a laser at F/4.75 (blue solid line) and when guiding on Alpha Cen A (red solid line). The blue and red dashed lines are linear fits to the data.

hence depending on guiding. This is especially true if the guiding system allows the light to reach the cladding of the fiber, which can happen if there is a slight misalignment between the hole used for guiding and the fiber itself.

This might be the cause of significant losses.

Position (in mm)	FWHM of gaussian fit (in mm)
0.0	9.2
7.3	10.6
10.75	11.4
13.3	11.8
14.9	12.1

Table 2: FRD measurement for the fiber used on CHIRON when guiding on Alpha Cen A

3 Spectrograph throughput

Using the laser feeding the science fiber at F/5, we plugged the fiber back into CHIRON and looked at the beam and the light path to see potential sources of loss.

3.1 Visual inspection

We have seen possible vignetting by the shutter but it could be a back-reflection that we see.

The iodine cell did not seem to vignet the beam further. However, the iodine cell motor failed to work and the cell needed to be pushed manually.

After the CFA, we noticed an odd shape (a little glitch in the round distribution), indicating possible vignetting (though very small). This might be present before the CFA, but the beam was too small to clearly see it.

The beam seems well centered on the collimator. It is slightly overfilling the collimator (by a few mm).

The beam on the collimator seems vignetted. It seemed to be due to L1. The bean on L1 seemed highly eccentric, but the current fiber holder does not allow to correct it, as we are limited in the number of degrees of freedom for the spectrograph alignment. Adding a tilt stage for the fiber should help.

3.2 Throughput measurement

Using the same laser and fiber feed, we have measured the power at different positions in the spectrograph using our power meter. We measured the power after L1, before the CFA, after the CFA and finally before the field flattener. The laser line seemed to fall onto the edge of the free spectral range (FSR) of the CCD, so we could see two distinct spots in the focal plane (and two additional spots outside the FSR). The power of these two spots were measured separately and then combined to yield the total power of the beam. Since the beam before the field flattener is much larger than the photodiode we used for the measurement, we needed to install a flat mirror to redirect the light where we could access the focus.

Table 3 summarizes our measurements. The spectrograph throughput should be given by the sum of the power of the two orders divided by the power before the CFA. This yields a spectrograph throughput of $(128 + 183)/803 = 38\%$, which is very close to the throughput calculated by A. Tokovinin in his efficiency report of March 28, 2011. In this report, a spectrograph throughput of 39% was found (excluding field flattener, L1 and L2). However, vignetting was not taken into account, since the measurements were done with a narrow beam. A lower throughput with a large beam was expected but not measured. This also shows that the possible loss candidates mentioned in Section 3.1 are negligible.

Power (in μW) (Meas. 1)	Power (in μW) (Meas. 2)	$\pm$ (in μW)	Position
800	820	20	After L1
805	800	10	Before CFA
760	770	20	After CFA
128	128	3	Bottom order
183	183	3	Top order
16	17	2	Sec. order (top)
12	12	2	Sec. order (bottom)
1.9			Line bet. spots

Table 3: Measurements of the spectrograph throughput.

4 Efficiency of the slicer and slits

Using the laser feeding the fiber at f/5, we have measured the relative efficiencies of the different observing modes by placing a power meter in front of the field flattener (with the help of a flat mirror). Table 4 summarizes the results. We see that the slicer efficiency is much lower than expected. This efficiency cannot be taken into account only by the blocking of he fourth slice. It could be the mirror coatings, scattering on the slicing edge and/or vignetting by the shutter edge. Most likely, it is a combination of all these effects.

Fiber (in μW)	Slicer (in μW)	Slit (in μW)	Narrow Slit (in μW)
168.5 ± 2	100 ± 2	49.7 ± 0.5	24.2 ± 0.3
1.0	**0.59**	**0.29**	**0.14**
172.2 ± 2	101.9 ± 1	49.7 ± 0.4	25.3 ± 0.5
1.0	**0.59**	**0.29**	**0.15**

Table 4: Efficiency of the slicer and of the slits.

5 Quantum efficiency of the detector

We estimated the quantum efficiency of the CCD in two different ways.

First we installed a diaphragm in front of the field flattener. We used the quartz lamp injected in the fiber that feeds CHIRON. We measured the power directly after the diaphragm with the power meter and then recorded a spectrum with the CCD using the same diaphragm. We subtracted the bias, counted all counts incident on each amplifier and multiplied by their respective gain to get the total number of photons on each side of the CCD. We added these to get the total number of photons.

$$N_{ph} = g_1 * C_1 + g_2 * C_2, \tag{2}$$

where g_1, g_2 are the gains and C_1, C_2 are the number of counts corresponding to both CCD amplifiers. To get the energy corresponding these photons, we assumed that they were all at a wavelength of $\lambda = 550$ nm. We have

$$E_{ph} = \frac{N_{ph}hc}{\lambda}, \tag{3}$$

where h is Planck constant and c is the speed of light. We then divide by the exposure time to find the power. We find a power of 24.9 pW.

In the second measurement, we have used the quartz lamp and a green filter going from 500 to 600 nm. We then measured the power right after the fiber and the power on the CCD (the same way we did it in the first measurement).

Table 5 summarizes the results. The quantum efficiency was calculated by dividing the power on the power meter by the power on the ccd. Additionally, we divided it in the first case by the efficiency of the field flattener (0.98) and in the second case by the measured efficiency of the spectrograph ($0.38 * 0.98 * 0.98 = 0.36$).

The measurements are probably not very precise but they are in agreement with the vendor data (85%). We then conclude that the quantum efficiency is not responsible for the bad efficiency that we have with CHIRON.

Power meter	Power on CCD	QE	Comments
28 pW	24.9 pW	90%	First meas., QE = 24.9/28./0.98 (field flattener)
4.78 nW	1.38 nW	80%	Sec. meas., QE = 1.38/4.78/0.36 (spectrograph)

Table 5: Efficiency of the slicer and of the slits.

6 Power measurement while guiding on Alpha Cen A

Using our power meter positioned right after the fiber and the green (500-600 nm) filter, we have recorded the power coming from Alpha Cen A as a function of time for a period of three hours (see Figure 2, only one hour is depicted).

The first thing to notice is how wild the power variations are. Over the three hours of data (only one hour is depicted in Figure 2), the power varied between 50 and 475 pW with an average at 221 pW. The maximum power of 475 pW is unexpectedly low. From previous calculations (see J. Spronck's document on Exposure Meter Photometry of May 11, 2011), we expected to have a power of 1.7 nW behind the fiber, which is 3.5 times more than the maximum value measured during this lapse of time. Possible explanations for this could be:

- Bad weather conditions: it was clear upon visual inspection, the seeing was reported to be good (0.75 on the Tololo weather page) but it was rather windy;
- Guiding losses: the large power variations might indicate important guiding losses. Can there be additional guiding losses up to a factor 3.5?
- Misalignment of the FEM: we have aligned the FEM as well as we could. The fiber image through the FEM viewer seemed round and centered. However, there is no focus adjustment in the FEM. Is it possible that the components have shifted in the z-direction?
- Error in the power estimate from a zero-th magnitude star: that could be possible and would also explain where our throughput disappeared; **We actually figured out that there is a mistake in the calculation. The collecting area of the telescope was counted to be 1.77 m^2. This does not include the obstruction from the secondary mirror though, which is 0.76 m in diameter. This would bring the collecting area down from 1.77 m^2 to 1.31 m^2 and the expected power from a zeroth magnitude star from 1.7 nW to 1.26 nW. The same mistake seems to be present in the document on CHIRON efficiency of March 28, 2011.**
- Power meter is not calibrated: possible.

Even if we could explain this factor 3.5, the average power is still twice lower than the maximum power. This additional factor is probably due to guiding/tracking errors. Indeed, we see in Figure 3 the power spectral density of the signal depicted in Figure 2. We clearly see a peak in the power spectral density a little short of 0.01 Hz, which corresponds to a period of $\approx$ 130 s, which can be seen in the power time series as well. We see large-amplitude oscillations with a period of $\approx$ 130 s. This is probably due to the tracking motor but should be corrected by the guiding system. This is important because it shows that there is a hardware solution to have a better throughput.

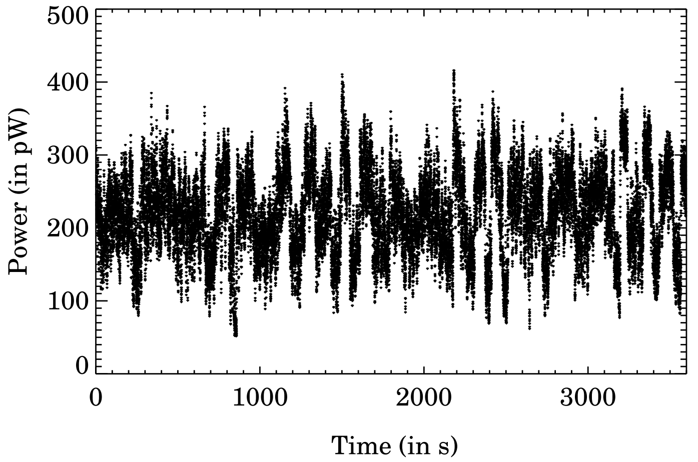

Figure 2: Power after the fiber when guiding on Alpha Cen A (airmass = 1.2) during one hour.

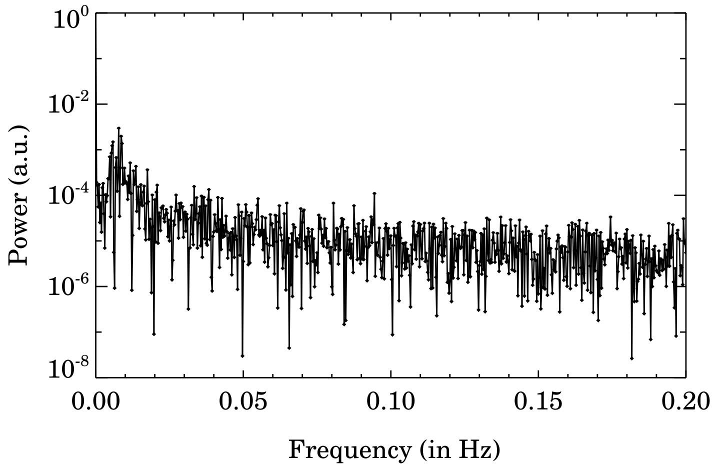

Figure 3: Power spectral density of the power depicted in Figure 2.

6.1 Power reaching the CCD

We took a set of 100 observations of Alpha Cen A with the fiber (exposure time of 6 s). For these observations, we also used the green filter (500-600 nm). For each observation, we calculated the power of the light reaching the CCD by repeating the method described in Section 5 (multiplying the total number of counts per amplifier by their respective gain, adding these up and transforming into power assuming that they all have the same wavelength).

Figure 4 depicts the total power reaching the CCD for all 100 consecutive observations. The average power per observation is 51 pW., which, when compared to the average power after the fiber (221 pW), gives a spectrograph efficiency of 23%. This is significantly lower than the efficiency found in Section 5, where we have performed the exact same measurement with the only difference being the light source. In Section 5, we had used the quartz lamp and found a spectrograph efficiency of 29%. This means that the spectrograph is 26% more efficient with the quartz lamp than it is with a star. This is probably due to different focal ratios for different light sources and means that the tests performed earlier in the week might not have been representative of the light losses in the case of star light. However, the FRD measurement when guiding on Alpha Cen A (see Section 2) is consistent with such losses.

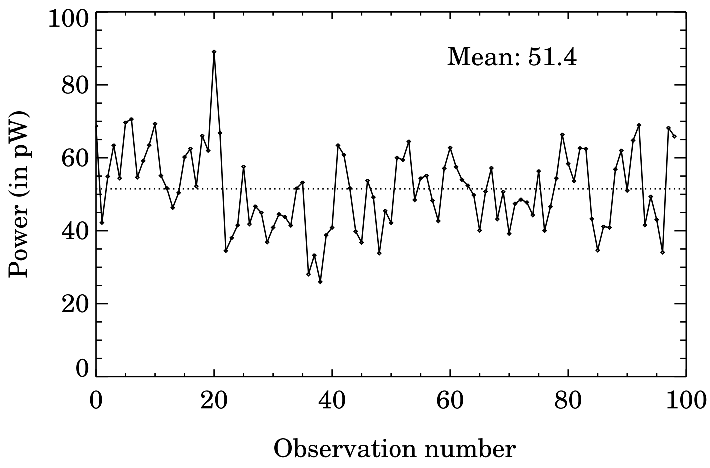

Figure 4: Total power on the CCD for 100 consecutive observations.

6.2 Mid-point variations

Due to the large amplitude of the power variations in Figure 2, there can be significant variations in mid-point times. To study this issue, we have considered 30-second chunks extracted from the hour of data depicted in Figure 2. For each 30-second chunk, we have calculated the weighted mid-point time based on the power incoming during these 30 seconds (see Figure 5). We see that due to the power variations, the mid-point time can change by up to 4 seconds for a 30-second observation. This could give an error in radial velocity of about 10 cm/s, showing the importance of using the exposure meter even for Alpha Cen observations (narrow slits observations of Alpha Cen A are 30 seconds long).

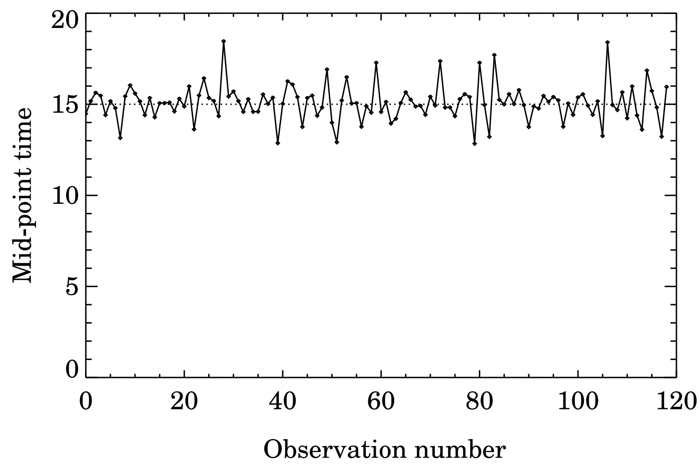

Figure 5: Mid-point time for 30-second "observations" spanning 1 hour.

7 Throughput of the iodine cell

The throughput of the iodine cell was measured with the laser beam. We found a throughput of only 56% when the cell was warmed up to 40 C.

8 Comparison with previous observations

We have run the program getpowerccd.pro on all Alpha Cen A observations in April and May. This programs returns the total power reaching the CCD (between 500 and 600 nm) for a given observation.

Figure 6 depicts the power for all Alpha Cen A observations since April 1st, 2011. All these observations have iodine. First thing to notice is that the power varies by a large amount, which is consistent with the measurements of Section 6. These large variations are probably due to weather changes, seeing variations and guiding/tracking errors.

In order to estimate the overall efficiency of the spectrograph, we need to know how much light to expect from Alpha Cen A above the atmosphere. According to Oke and Schild, 1970 (The Absolute Spectral Energy Distribution of Alpha Lyrae) and Schild et al., 1971, Alpha Lyrae radiates $3.64\ 10^{-8}\ J/m^2/s/\mu$m (of wavelength) above the atmosphere of the Earth at a wavelength of 0.548 μm. The band-pass filter that we will use in front of the PMT has a FWHM of $\approx$ 80 nm, which gives $E = 2.9\ 10^{-9}\ J/m^2/s$. For a 1.5 m telescope with a 76 cm central obstruction (area = 1.31 m^2), we have $P = 3.8\ 10^{-9}\ W = 3.8\ nW$. This is the power captured by the 1.5-m telescope in a 80-nm band for a 0^{th} magnitude star above the atmosphere.

Using this number and the numbers that we measured in Section 7 for the iodine cell throughput and in Section 4 for the efficiency of the slicer and the narrow slit, we can plot the overall spectrograph efficiency (from atmosphere to detector) as a function of time (see Figure 7). The fact that the blue and red curve overlap well is a sign that variations are mainly due to weather conditions. The fluctuations within a night can also be weather/seeing related but are most likely due to guiding/tracking errors. We see that the overall spectrograph efficiency tops at $11-12\%$, indicating that there is nothing wrong with the spectrograph efficiency. And that the previously calculated efficiency was simply underestimated.

However, the weather/guiding averaged efficiency is closer to 8%. There is not much we can do about the weather but guiding could be improved if we need to get higher efficiencies.

The other thing to note is that the efficiency dropped considerably the two days after our visit (June 12 and 13), indicating some misalignment that should be fixed. A longer baseline is needed to see whether this lower efficiency is not weather related. However, in the last two months, there is no history of such a low throughput for two days in a row.

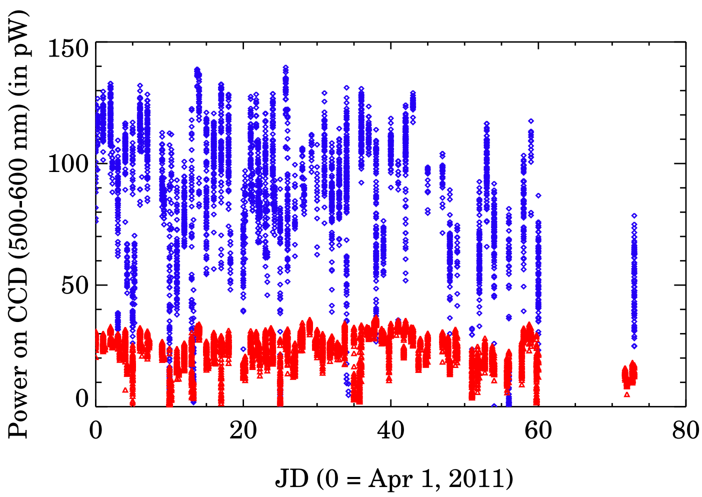

Figure 6: Power reaching the CCD for all Alpha Cen A observations since April 1st, 2011. Red triangles and blue diamond correspond respectively to narrow slit and slicer observations.

9 Conclusions

We have thoroughly tested the efficiency of the spectrograph and have found a few interesting things:

- The fiber currently used on CHIRON was measured to be the best fiber in terms of FRD and as good as other fibers in terms of transmission.

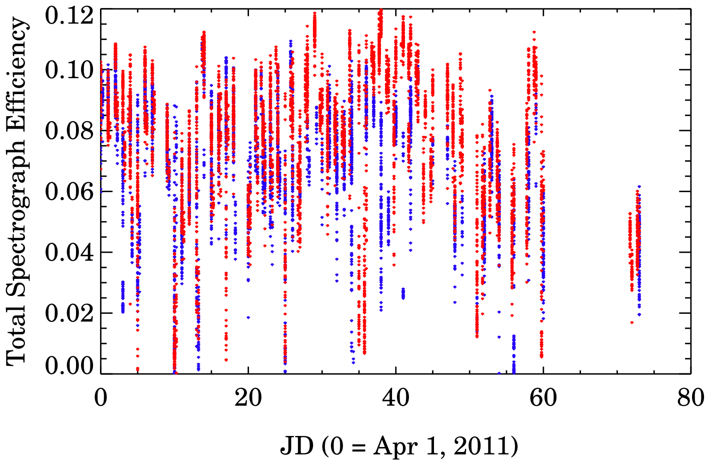

Figure 7: Overall spectrograph efficiency since April 1st, 2011. Red triangles and blue diamond correspond respectively to narrow slit and slicer observations.

- The FRD was worse than expected when guiding on Alpha Cen A, probably yielding 26% losses when compared to the efficiency measured with the quartz lamp.
- The quantum efficiency of the detector was measured to be as expected ($80 - 90\%$).
- The slicer has an unacceptably low throughput of 59%.
- The iodine cell when warmed at 40 C has a throughput of only 56%.
- We found large amplitude power variations coming from the star, with a clear period at ≈ 130 s. There should be a hardware solution to minimize this effect.
- These large amplitude power fluctuations make the use of an exposure meter necessary even for Alpha Cen observations.
- The previous value measured for the spectrograph efficiency seemed underestimated. The peak overall spectrograph efficiency was calculated to be as high as expected ($\approx 12\%$).
- The spectrograph seems to currently have a lower efficiency than it has had in the past.