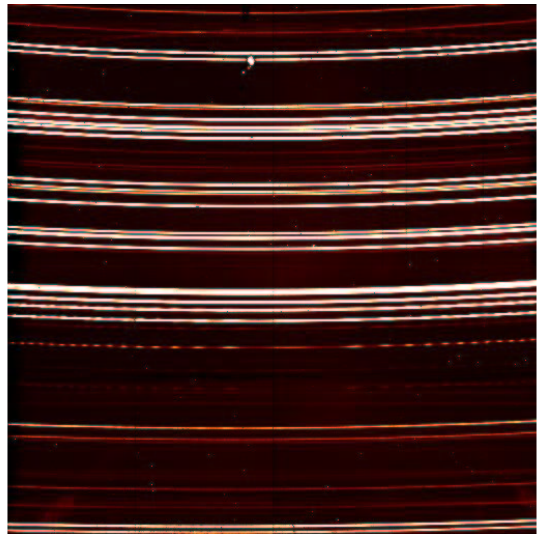
Spectroscopy at the NOT
Current instrument status and possible efficiency/functionality upgrades



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1 Introduction and document scope

The spectroscopic capabilities of the astronomical instruments of the NOT are of great interest to the Nordic astronomical cummunity. This is evident from the fact that half the number of proposals for the P29 and P30 semesters in 2004 applied for observing time to do spectroscopy.

Currently the spectroscopic instrument suite available to the Nordic community consists of ALFOSC (low-res optical), NOTCAM (low-res near-IR), and SOFIN (high-res optical). The fiber-fed high-res optical spectrograph FIES is now equipped with a good detector, and will be developed into a common-user instrument.

Although the current instrumentation is very attactive for the user community, it is my personal conviction that to keep the spectroscopic capabilities of the NOT attractive for the near future, say a few years, we will have to keep developing the functionality and the efficiency of the available instruments, such that the NOT will offer new kinds of science and/or the ability to observe fainter sources.

In this document I review the current spectroscopic capabilities of the NOT, discuss planned upgrades, and discuss further possibilities for upgrading instrument functionality and efficiency.

2 Current instrument status, functionality and efficiency

The total system efficiencies mentioned in this section, and throughout this document, include atmosphere, telescope, slit-losses, instrument and detector. For ALFOSC and SOFIN the system efficiencies were measured with wide-slit flux-standard observations. For FIES flux-standard observations were used as well. The slit and fiber losses were computed for a Gaussian seeing of 0.8 arcsec (more or less the median seeing at ORM in the optical) and 0.6 arcsec for NOTCam.

The peak efficiencies are for a given resolution, and stand for the highest efficiency for that resolution found in the complete wavelength range offered by the considered instrument. For optical instruments the peak efficiencies are reached in the BVR domain: U, I and Z efficiencies are much lower. For NOTcam the peak efficiency is reached in the HK bands, but Z and J efficiencies are *not* much lower.

I use the term 'instrument functionality' to express its ability to cover wavelength range and spectral resolution.

2.1 ALFOSC

- Capabilities: long-slit spectroscopy; multi-object spectroscopy (MOS); linear and circular spectropolarimetry (using FAPOL)
- System efficiency and spectral resolution: ∼24% @ R=100, ∼6% @ R=4500
- Wavelength coverage: 3200Å – 11000Å
- Science: redshifts, spectral energy distribution, spectral classification, radial-velocity variations, velocity dispersions, low-res abundance studies, etc.
- Recent upgrades: order-blocking filters, new blue grism #16 (R=900 for a 1-arcsec slit)

The system efficiency for the spectral resolution range R=100–1000 (using a 1-arcsec slit) compares well with that of FORS1+VLT1, ISIS+WHT, and DOLORES+TNG. The ALFOSC grisms that give these resolutions have peak grism efficiencies of 60–75%.

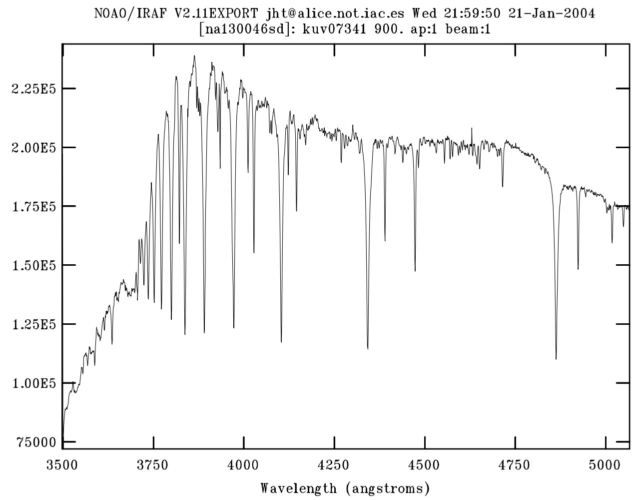

Figure 1: Example spectrum taken with the recently commisioned ALFOSC grism #16: a sub-dwarf B star

Resolutions between R=1000–4500 are reached by using narrow slits or by using the cross-dispersed Echelle mode. The combined peak grism efficiency of the Echelle grism and any of the cross-dispersing grisms is less than 30%.

2.2 NOTcam

- Capabilities: long-slit spectroscopy; linear spectropolarimetry
- System efficiency and spectral resolution: ∼6% @ R=2000
- Wavelength coverage: JHK
- Science: redshifts, spectral classification, velocity dispersions, radial-velocity variations, etc.
- Recent upgrades: Echelle grism (R∼2000 with Wide Field Camera), slits for WFC (appropriately mounted in new holders), first light

The spectroscopic system efficiency is based on very few flux-standard star observations, and will have to be confirmed. The system efficiency is comparable with ISAAC+VLT1 and NICS+TNG, but somewhat on the low side due to the grism efficiency. Note that the observed JHK efficiency of NOTcam with its Wide Field Camera in *imaging* mode compares very well to those of similar instruments on different telescopes.

Currently there is only one grism in NOTcam. The peak grism efficiency of this Echelle grism is only 40%.

Note that the J band is sampled on the detector in two spectral orders (see top panel in Figure 2). The 2 orders have different dispersions, but have some spectral overlap. Wavelength calibration of the short-wavelength order will be difficult due to limited coverage. The 'bluest' 300Å of the J-band are affected by this problem.

The best slit that is currently available projects to ∼2.6 pixels using the WFC, which is equivalent to 0.6 arcsec.

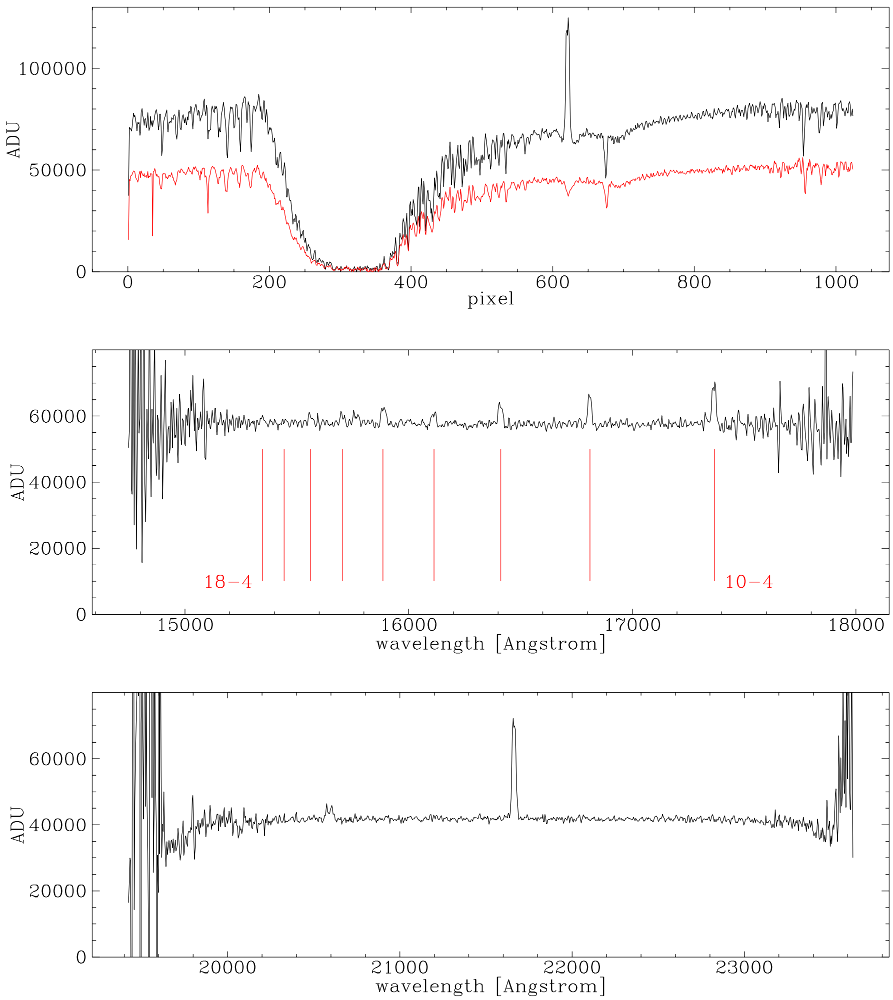

Figure 2: NOTcam spectroscopy: first-light spectra of the Be star 66 Oph, showing strong emission in Paschen and Brackets series. Top: J-band spectrum of 66 Oph and a ratio-ing F-star. Middle: H-band spectrum of 66 Oph after division by F-star spectrum. Bottom: as middle for Ks band.

2.3 SOFIN

- Capabilities: short-slit spectroscopy; spectropolarimetry
- System efficiency and spectral resolution: ∼5% @ R=37000, ∼1% @ R=162000
- Tunable wavelength coverage: 3700Å – 10500Å (no order overlap!!)
- Science: abundance studies, accurate radial-velocity variations, line-profile variations, interstellar lines, etc.
- Recent upgrades: new coatings, new Loral detector, new cross-disperser
- Development and support: Dr. I. Ilyin

The lowest spectral resolution mentioned above, corresponds to a 1-arcsec slit. The resolution obtained with wider slits is seeing dependent. Depending on the chosen spectral resolution (there are 3 different cameras), the entire optical range can be sampled in 2 to upto tens of exposures.

The system efficiency does not compare well to that of UVES+VLT ∼9% @ R=62000, SARG+

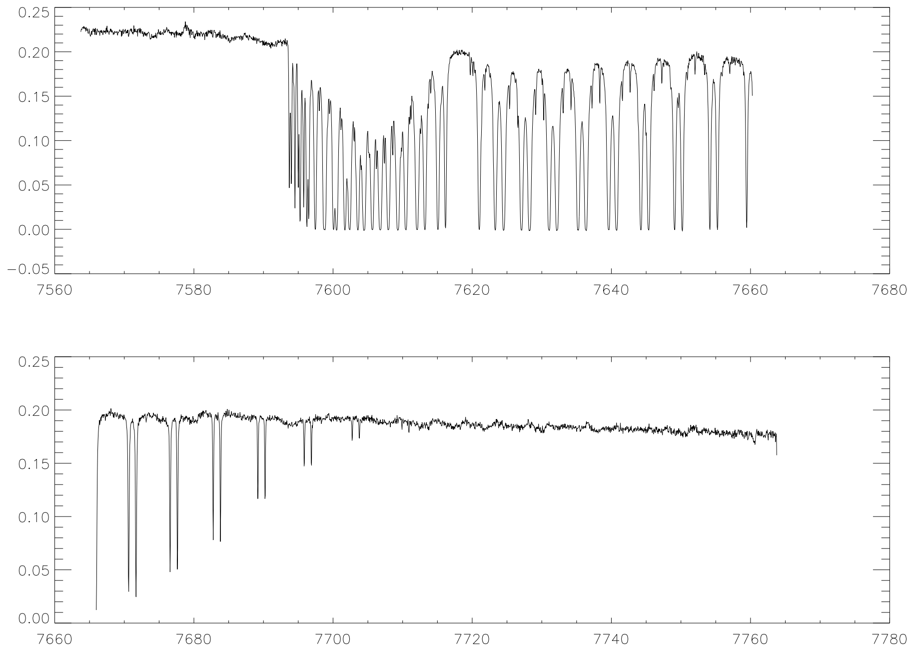

Figure 3: Example spectrum taken recently with FIES, showing telluric O_2 absorption lines

TNG ∼9% @ R=57000, FEROS+2.2m ∼15% @ R=48000.

It is possible to observe with SOFIN in the 1-μm region at efficiency below 1% with an old thick EEV chip with relatively low fringe levels.

The new cross-disperser enables simultaneous polarisation measurements of beam-split stellar images.

SOFIN is not a common-user instrument: all support and development is carried out by Ilya Ilyin.

2.4 FIES

- Capabilities: fiber-fed spectroscopy
- System efficiency and spectral resolution: ∼3% @ R=60000
- Wavelength coverage: 3800Å – 8400Å (with order overlap!!)
- Science: abundance studies, accurate radial-velocity variations, line-profile variations, etc.
- Recent upgrades: new E2V detector, new skew read-out mode
- Development: Dr. S. Frandsen / NOT

The system efficiency does not compare well to that of UVES+VLT ∼9% @ R=62000, SARG+TNG ∼9% @ R=57000, FEROS+2.2m ∼15% @ R=48000.

The skew readout mode was developed by Arto Järvinen at the NOT, with the purpose of doing intermediate-resolution stand-by spectroscopy of relatively faint objects. The skew readout mode accounts for the curvature of the orders, in order to enable very coarse binning to suppress read-out noise.

FIES is to be developed into a common-user stand-by instrument. For FIES a pipe-line reduction

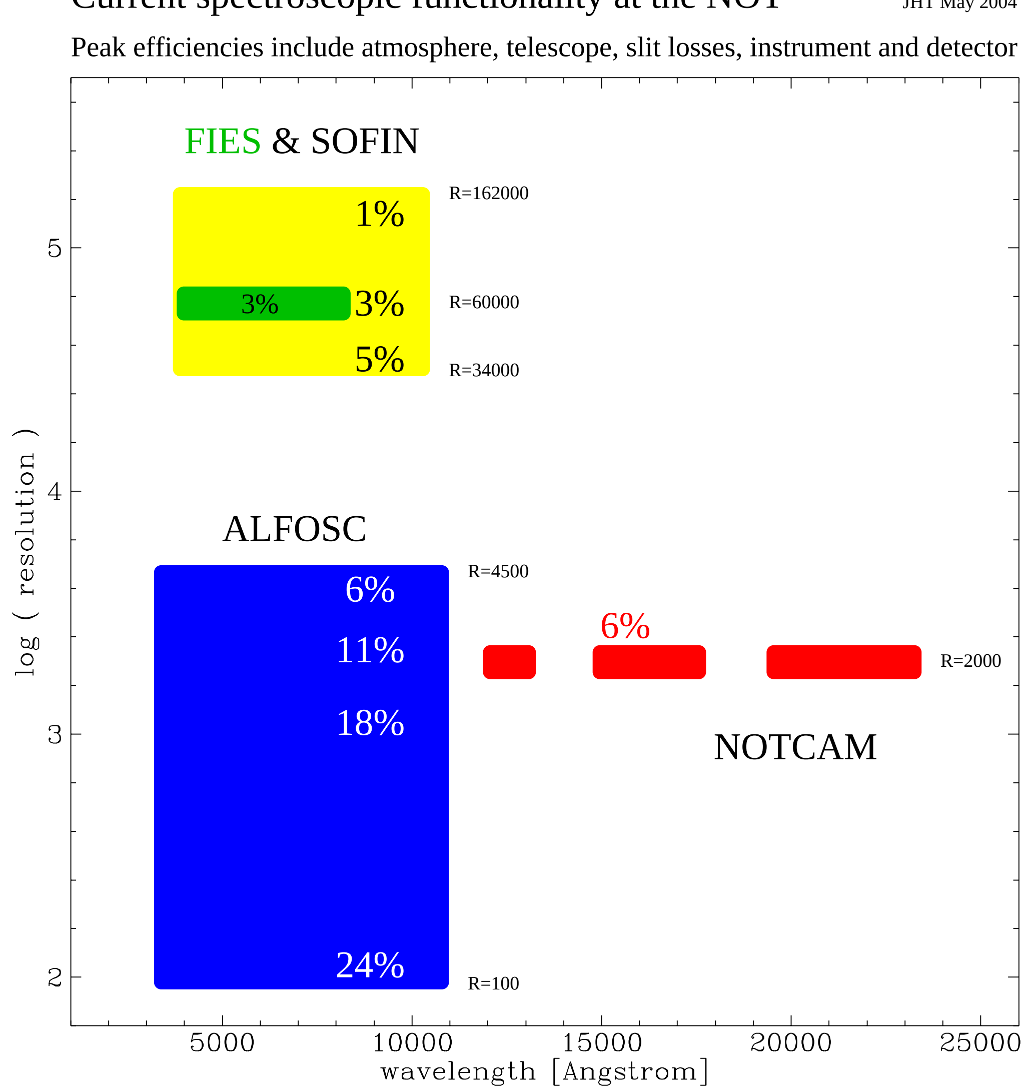

Figure 4: Current spectroscopic functionality and peak efficiency in a plot of spectral resolution versus wavelength. Note that SOFIN is depicted as yellow; FIES as green.

is being developed by Eric Stempels at the NOT.

3 Overview of current spectroscopic instrumentation

Figure 4 shows an overview of the current functionality and efficiency of the spectroscopic instruments at the NOT. The peak efficiencies are indicated in the plot, and stand for the highest efficiency found in the complete wavelength range offered by the considered instrument for a given resolution.

Given the quantum efficiencies of the optical items involved (atmosphere and detector included), an efficiency figure higher than 20% will be hard to improve. From figure 4 it is clear that there are quite some places in the diagram where such high efficiencies are not the case, and hence where significant improvements may be achieved.

In particular the grism efficiency of the Echelle grisms in ALFOSC is quite low, and it is worth while investigating if major improvements can be expected from using Volume Phased Holographic (VPH) grisms to replace the Echelle mode.

Similarly, the system efficiency of the high-resolution spectrographs FIES and SOFIN is not very high. The peak efficiency of NOTcam is affected by the relatively low quantum-efficiency of the

HAWAII detector of 60% (HK bands) and 45% (1 μm and J band).

3.1 No overlap between ALFOSC and SOFIN/FIES

There is currently a gap in resolution coverage in the optical domain. This gap constitutes the spectral resolutions between R=10000–25000. Types of science corresponding to the gap: detailed galaxy dynamics, abundance studies of relatively faint stars, accurate orbital velocity studies in binaries, emission line morphology, pulsational line-profile variations in relatively faint stars, etc.

VPH grisms could be of benefit to increase the functionality of ALFOSC to spectral resolutions as high as R=12000 at very high efficiency.

3.2 Overlap between ALFOSC and NOTcam

In principle, there is overlap in the spectral coverage of ALFOSC and NOTcam, in the region between 8000–11000Å. Currently however, NOTcam is not equiped with wide-band filters in this spectral domain, and hence has no spectroscopic functionality at these wavelengths.

Note that the system efficiency of NOTcam spectroscopy at 0.85–1.0 μm is about 4% with the current Echelle grism. ALFOSC system efficiency is about 4% at 0.9 μm and 1% at 1.0 μm. This means that NOTcam is expected to be a factor 3 to 5 better in this region around 1.0 μm. In detector efficiency NOTcam (HAWAII detector) is a factor 4 times better than ALFOSC (E2V detector) around 1.0 μm.

For wavelengths larger than 0.85 μm, the fringe levels on the E2V chip in ALFOSC are ∼50% peak-to-peak, whereas fringe levels on the HAWAII array in NOTcam are ∼15% peak-to-peak.

Therefore it will be advantageous if NOTcam were to be equiped with appropriate filters and grisms to increase its functionality in the Z band, in order to significantly improve efficiency with respect to ALFOSC and with significantly lower fringe levels than ALFOSC+E2V.

4 Planned upgrades of the instruments

4.1 FIES upgrades

• New location in a building at the telescope base, will lower efficiency by factor ∼0.8 due to increased fiber length, but will increase spectrograph stability.

• New fibers: one low-res (R=30000) and one high-res (R=60000). For the low-res fiber the system efficiency will boost by a factor ∼1.6, as there is no need for a slit at the fiber exit.

• New coatings will boost efficiency by factor ∼1.7

• New couplings between telescope and fiber, and between fiber and spectrograph: increase efficiency by factor ∼1.2

Total efficiency boost: factor ∼1.6 (high-res) and factor ∼2.6 (low-res)

Estimated delivery time: ∼ 1 year.

• New calibration unit !! With FIES in the new building, and with new fibers fixed at Cassegrain, a dedicated calibration unit has to be designed for illuminating the fiber entrance inside the adapter with Halogen and ThAr light.

5 Suggestions for further upgrades of the instruments

5.1 ALFOSC: suggestions for upgrades

• New R=6000 – 12000 medium-res spectroscopy

Michael Andersen suggests a 2620 g/mm VPH 'Dickson' grism with high grism efficiency of ∼90%. Wavelength range 400Å around Hα. Dispersion 0.2 Å/pixel. This will give a total system efficiency at R=6000 of ∼29%, i.e. ∼5 times that of the current Echelle mode at R=4500. Note that the ISIS+WHT efficiency at R=6000 is 12%, implying that NOT+ALFOSC will give as many detected photons as WHT+ISIS.

At R=12000 (0.5 arcsec slit) the system efficiency will be about 18%. Note that the ISIS+WHT efficiency at R=12000 is 8%, and that there is no other instrument on La Palma offering this spectral resolution.

Expected cost for NOT: 6000 Euro. Delivery time: Aug 2004.

• Boost R=2000 – 5000 spectroscopy

As an alternative Michael Andersen suggests a 1500 g/mm VPH grism with high grism efficiency of ∼90%. Wavelength range 1100Å around Hα. Dispersion 0.53 Å/pixel. This will give a total system efficiency at R=2000 of ∼29%, i.e. ∼2.2 times that of the current Grism #8.

At R=5000 (0.5 arcsec slit) the system efficiency will be about 18%. i.e. ∼3 times that of the current Echelle mode.

Expected cost: 5000 Euro per grism. Estimated delivery and installation time: 6 months. It needs to be investigated whether a suite of 4 to 5 of such grisms can deliver high efficiency over the full ALFOSC UBVRI wavelength range, in order to replace the low-efficiency Echelle mode.

Science drivers for the above suggested ALFOSC upgrades: detailed galaxy dynamics, abundance studies of relatively faint stars, accurate orbital velocity studies in binaries, emission line morphology, pulsational line-profile variations in relatively faint stars, etc.

5.2 NOTcam: suggestions for upgrades

• NOTcam Calibration unit (phase 1)

Currently there is no possibility of wavelength calibrating J and Z-narrow (1μm) band spectra. In H and K band skylines can be used for wavelength calibration, requiring long exposures. The ability to get ZJ wavelength calibration is needed to offer NOTcam spectroscopy as a common-user instrument in observing semester P30 in 2004.

We have obtained good wavelength calibration spectra in JHK with a new Argon lamp mounted in the telescope baffle (see Figure 5). The new lamp(s) need to be properly mounted on the baffle lid, with manual on/off switches in the telescope control room. One of the downsides of this configuration is that the mirror covers have to be closed to obtain calibration spectra with NOTcam.

Estimated time needed for completion: few months.

• NOTcam Calibration unit (phase 2)

New mechanically retractable mounting on top of baffle, with full computer control to put the unit in and out of the beam, and with full computer control to switch on/off lamps. The baffle mechanism should be independent of the telescope mirror petals mechanism.

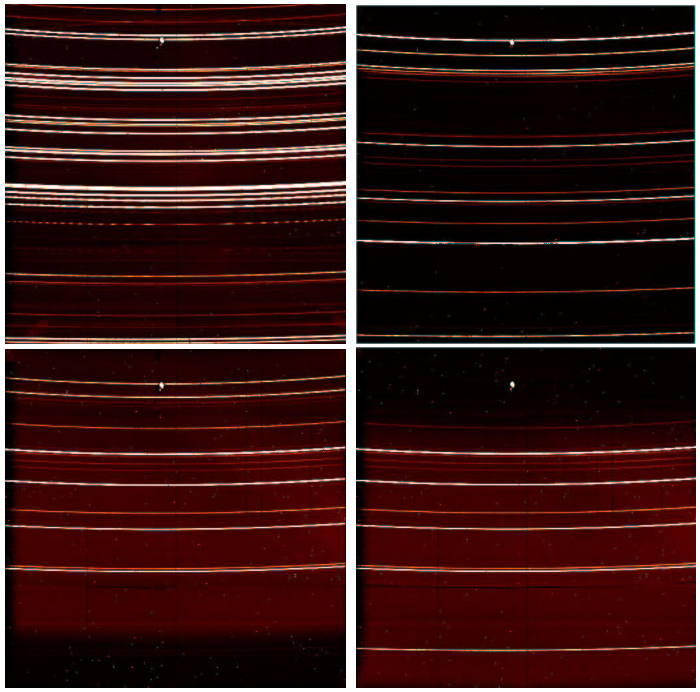

Figure 5: NOTcam Argon spectra taken with recently purchased calibration lamps. The high cuts are at 4000 ADU and the exposure times were 10 seconds. Top: J and H band. Bottom: K' and K band

- New NOTcam R=6000 spectroscopic mode

Using the High Resolution Camera (HRC) instead of the Wide Field Camera (WFC) will boost the spectral resolution by a factor 3 to R=6000. Wavelength ranges sampled by the detector will be 3 times less, for the current grism. Expected system efficiency: ~4%

Currently, the HRC can not be focussed. This can be remedied by machining 2mm off the aperture wheel assembly, or by 'repair' of the HRC itself. The latter option needs outsourcing, and will affect the properties of the HRC in imaging mode. Therefore the first option is preferred.

Science drivers for this suggested NOTcam upgrade: detailed galaxy dynamics, abundance studies of relatively faint stars, orbital velocity studies in binaries, emission line morphology, etc.

Cost: 0 Euro. Estimated time needed: few months.

- New R=2000 grism

This in order to sample J and Z-narrow (1μm) orders centrally on the detector. The current grism splits the 1μm band exactly in the middle, such that two half spectral orders are imaged on the array. As can be seen in Figure 2, also the J band spectra are affected by this problem.

If proper J and 1μm-band coverage with R=2000 is desired, then a wavelength-shifted copy of the current Echelle grism can be designed. Expected system efficiency: ~5% (i.e. 4 times better than ALFOSC at 1μm)

Cost for grism: 5000 Euro. Estimated delivery time: 6 months.

- New R=700 low-res spectroscopic mode for NOTcam

A new R=700 low-res spectroscopic mode for NOTcam will bring the possibility to do the following types of science in the NIR: redshifts, spectral energy distribution, spectral classification, low-res radial-velocity variations, velocity dispersions, low-res abundance studies, etc.

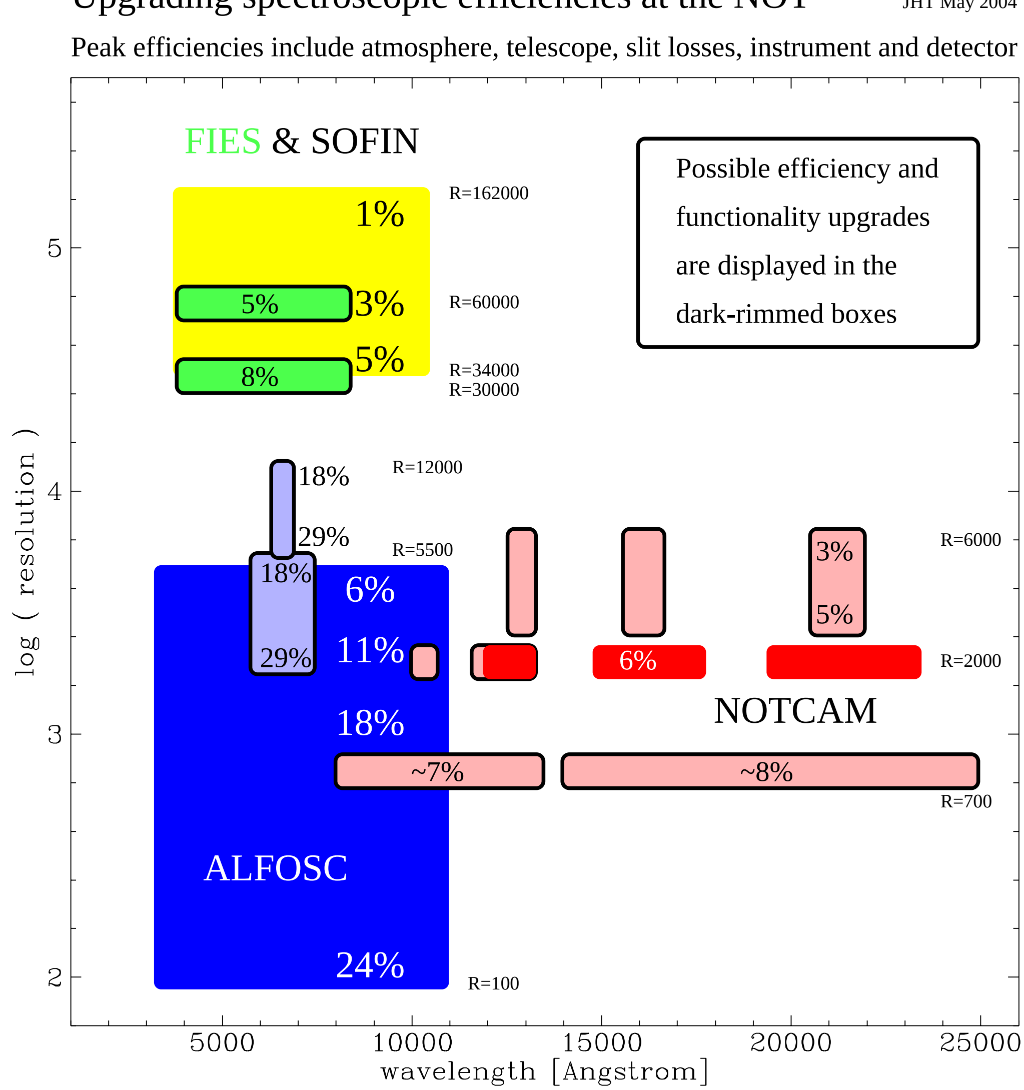

Figure 6: Spectroscopic functionality and peak efficiency in a plot of spectral resolution versus wavelength. Note that SOFIN is depicted as yellow; FIES as green. Planned and suggested upgrades are depicted in dark-rimmed boxes. Note that a full upgrade of the R=2000–5000 ALFOSC Echelle mode can be achieved with a set of 4 or 5 VPH grisms covering 3500–8000Å, of which only the one around Hα is shown in the diagram

Both in terms of efficiency and in terms of fringe levels, NOTcam will be advantageous to use over ALFOSC in the 0.85-1.1μmicron range (see Section 3.2).

The R=700 mode can be achieved with 1 new grism and 2 or 3 filters (see table below). The HK filter is already inside NOTcam, but without a matching grism it currently serves no purpose. Expected total system efficiency: ~8%.

HK 14000–25000Å	1st order only	filter already inside NOTcam
JH 10500–19000Å	1st + 2nd order	needs new filter
ZJ 8000 –13500Å	2nd order only	needs new filter

Cost per filter: 2500 Euro. Cost for grism: 5000 Euro. Estimated delivery time: 1 year for the new filters and a few months for the grism.

Note that a low-resolution R=100 mode in NOTcam that samples ZJHK in one spectrum will *not* be possible due to the chromatic focus variations of the instrument.

6 Overview of planned/suggested upgrades of our spectroscopic instrumentation

In Figure 6 I have plotted the discussed upgrades on top of the current instrument functionality. It is obvious that in parts of the spectral-resolution versus wavelength plane significant efficiency and functionality improvements can be achieved. In case of the suggested upgrades for ALFOSC and NOTcam, these improvements can be realized for modests costs and on short timescales.

7 Conclusions and recommendations

• Planned FIES upgrades will increase the system efficiency to ∼5% at R=60000 and ∼8% at R=30000, and will improve spectrograph stability.

• ALFOSC R=6000–12000 medium-resolution spectroscopy at high system efficiency is possible with VPH grisms. Currently, the NOT does not have optical medium-res spectroscopy in its instrument suite.

• ALFOSC R=2000–5000 spectroscopy: the current ALFOSC Echelle mode may be replaced by a set of VPH grisms, giving a factor 3 increase in efficiency. We should investigate this possible upgrade in detail.

• NOTcam versus ALFOSC: in the wavelength range 0.85–1.1μm, NOTcam spectroscopy is expected to out-do ALFSOC by a factor of ∼4 in efficiency with about 3 times lower fringe levels (for the current HAWAII and E2V detectors). Currently, NOTcam does not have appropriate filters and grisms to take advantage of its potential in this wavelength region.

• A low-res R=700 mode in NOTcam can be acquired in order to extend the typical types of science done with ALFOSC to the wavelength domain 0.85–2.5μm. This can be achieved with 1 new grism and 1 or 2 new filters for NOTcam.

• An R=6000 medium-resolution mode in NOTcam can be achieved by a mechanical fix of the aperture wheel assembly.

• Optimal sampling of the J and 1μm bands at R=2000 can be achieved by the purchase of a wavelength-shifted copy of the current Echelle grism in NOTcam. Currently, these bands are imaged on the detector in incomplete off-center spectral orders, which makes proper wavelength calibration and spectral analysis more difficult.

• NOTcam needs a calibration unit in order to get the status of a common-user spectrograph.