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FIES: The high-resolution Fiber-fed Echelle Spectrograph at the Nordic Optical Telescope

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FIES is a cross-dispersed high-resolution echelle spectrograph at the 2.56 m Nordic Optical Telescope (NOT), and was optimised for throughput and stability in 2006. The major 2006 upgrade involved the relocation of FIES to a stable environment and development of a fiber bundle that offers 3 different resolution modes, and made FIES an attractive tool for the user community of the NOT. Radial-velocity stability is achieved through double-chamber active temperature control. A dedicated data reduction tool, FIEStool, was developed. As a result of these upgrades, FIES is now one of the work-horse instruments at the NOT.

1 Introduction

FIES[1] is a cross-dispersed high-resolution echelle spectrograph at the 2.56 m Nordic Optical Telescope (NOT; Djupvik & Andersen 2010). FIES was originally mounted on the telescope fork (see Frandsen & Lindberg 2000), with two fibers simultaneously feeding the spectrograph, offering only one resolution mode. To isolate it from sources of thermal and mechanical instability, FIES was installed in a heavily insulated building separate from and adjacent to the NOT dome, in 2006.

The optical fibers that connect the telescope with the spectrograph are permanently mounted with a movable 45 degree tertiary mirror near the focal plane of the telescope. The fibers run from the telescope through the azimuth axis to the spectrograph enclosure.

The currently installed fiber bundle contains three 1.″3 fibers offering spectral resolutions of $R = 67\,000$ (high-resolution mode: HIGH-RES) and $R = 46\,000$ (medium-resolution mode: MED-RES), and a fiber with a larger entrance aperture of 2.″5 but a lower spectral resolution of $R = 25\,000$ (low-resolution mode: LOW-RES). The entire spectral range 370–730 nm is covered without gaps in a single, fixed setting. FIES offers the option of simultaneous observations of wavelength reference thorium-argon (ThAr) spectra, for the MED-RES and HIGH-RES modes. Simultaneous sky spectra can be obtained in MED-RES mode, restricted to wavelengths shorter than 650 nm.

An exposure meter is available to predict the S/N of an ongoing exposure, allowing to optimise the exposure time. FIES can be used with or without the atmospheric dispersion corrector. Being a permanently mounted instrument, FIES can be used at any time, also for short periods of time while other instruments are mounted.

In order to complete the move in 2006 to its current environment, a new fiber bundle had to be developed, which has never been described in the literature. Currently we are using the third version of this bundle, called bundle C, that we describe in this paper. The spectrograph design was described by Frandsen & Lindberg (1999), and is concisely reviewed in this paper. Furthermore, we describe the stability and efficiency of the FIES + NOT system, and touch on the importance of FIES for the user community of the NOT.

2 Spectrograph design

The spectrograph is of white-pupil design (see Fig. 2; Baranne et al. 1972; Dekker et al. 2000) with two off-axis collimators, the first of which is double pass. The fiber unit is coupled to a focal-extender lens that narrows the beam to

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[1] FIES: http://www.not.iac.es/instruments/fies/

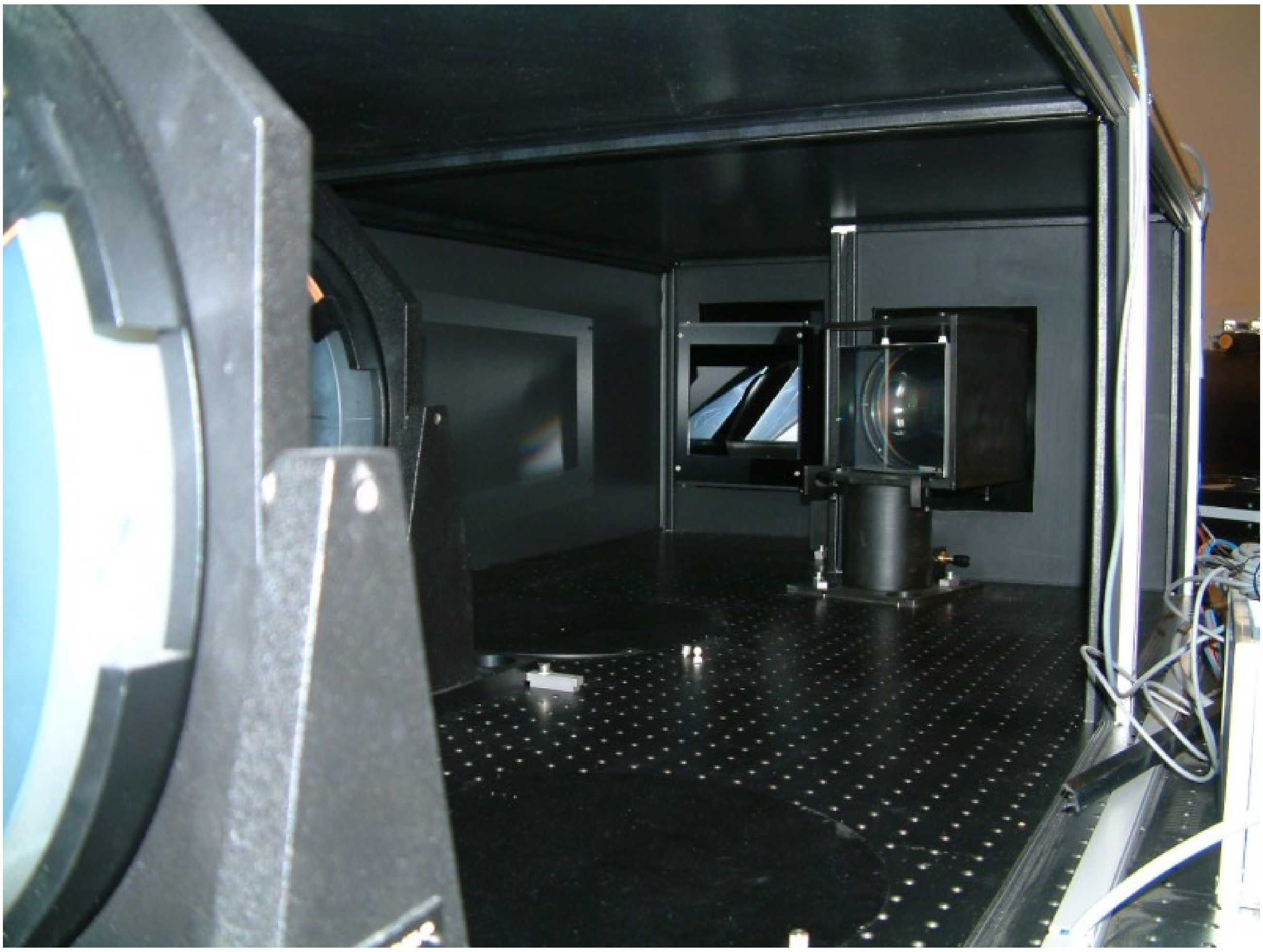

Fig. 1 View into the spectrograph when opened; on the left the two off-axis collimators seen from behind; on the right the shiny grating, and even further right the cross disperser. The exposure meter was not yet installed at the time this picture was taken.

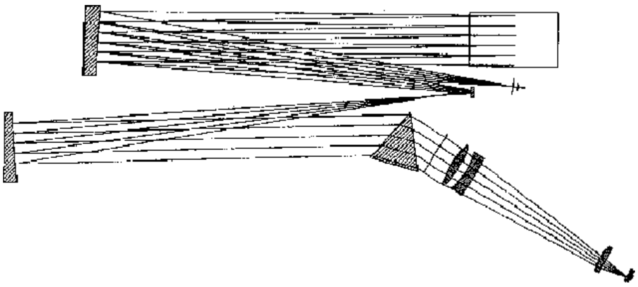

Fig. 2 Schematic of the optical design of the spectrograph.

limit losses on the grating. When entering the spectrograph the light passes the 1-inch iris shutter used for timing the exposures. The 31.6 grooves mm^{-1} échelle grating is mounted at 63.5 degrees and has a ruled area of 154×306 mm. At the small folding mirror the exposure meter picks off light that otherwise would not reach the CCD. The cross-disperser is a monolithic 48 degree prism. A picture of the collimators and dispersers is presented in Fig. 1.

The camera is equipped with a coarse focus drive, and images the 100 μm fibers onto about 4 pixels on the CCD at F/3.0. A more complete description of the spectrograph design is given by Frandsen & Lindberg (1999).

The camera-focus drive and the spectrograph and exposure-meter shutters are the only movable parts that can be operated under computer control. Only the shutters are operated at a regular basis. FIES is offered in one fixed wavelength setting only.

The current 2k×2k 13.5μm pixel e2v CCD42-40 CCD samples the wavelength region of 370–730 nm, whereas the spectrograph optics are designed for a wider wavelength range. The dispersion ranges from 0.023 Å pixel^{-1} in the blue to 0.045 Å pixel^{-1} in the red.

3 The fiber bundle and calibration units

The fiber unit consists of 5 fibers of Polymicro FPB type with circular cross-section: a 200 μm fiber for the LOW-RES $R = 25\,000$ mode, two 100 μm fibers for the MED-RES target + sky $R = 46\,000$ mode, one 100 μm fiber for simultaneous ThAr light, and one 100 μm fiber for the HIGH-RES $R = 67\,000$ mode. The high resolution is achieved by a 50 μm exit slit on both the HIGH-RES and the simultane-

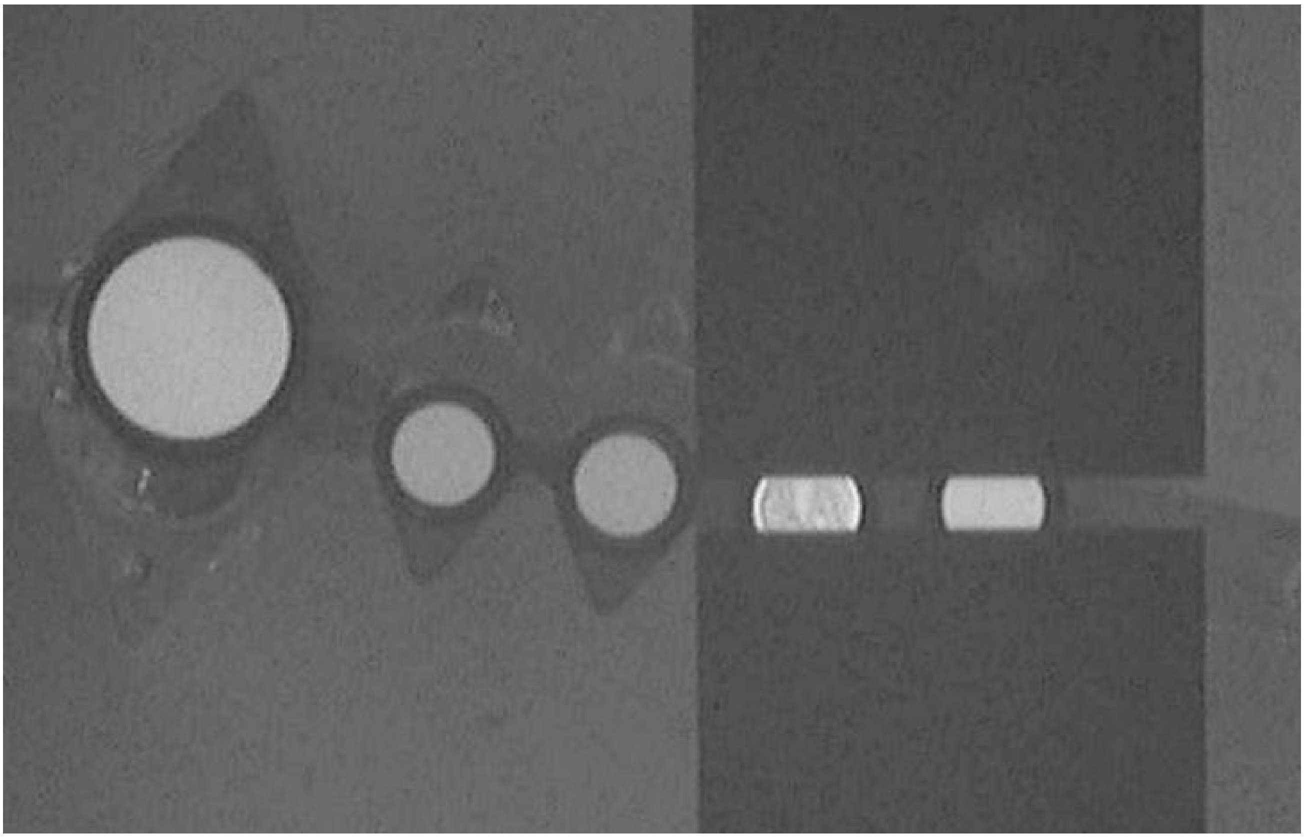

Fig. 3 All fibers, simultaneously illuminated, seen at the spectrograph end. *From left to right*: 200 μm low-resolution fiber; 100 μm med-resolution sky and target fibers; high-resolution simultaneous ThAr and target fibers, both with the common 50 μm slit.

ous ThAr fibers at the expense of about 40 % of the light. A picture of the fiber coupling at the spectrograph end is presented in Fig. 3.

At the telescope the 4 fibers that view the sky have the telescope pupil projected onto the fiber entrance in order to maximise throughput. These 4 fibers can be illuminated by ThAr or halogen lamps located in a calibration unit under the telescope's mirror cell, for wavelength calibration and flatfielding. When a fiber is not in use, its entrance is blocked by a mask to avoid unwanted sky light in the spectrograph. The simultaneous ThAr fiber has a separate calibration unit near the spectrograph.

4 Instrument stability

4.1 Radial-velocity (RV) stability

In its protected building the instrument is kept at a stable temperature within 0.02 K. To achieve this the dispersive elements and the collimators are sealed in a single separate compartment (see Fig. 1). This compartment, the spectrograph camera, CCD cryostat and controller, and the fiber bundle coupling, are all mounted on the optical bench, and are sealed by another surrounding box made of isolation material. Inside this second box the temperature is actively controlled. The box holding the spectrograph is mounted in a dedicated spectrograph room, which itself is also under active temperature control.

We do not actively cool the spectrograph nor the spectrograph room. Heat produced by the CCD-controller is ducted out of the spectrograph box, into the main spectrograph room. Heat produced by the CCD cooler (Cryotiger) is dissipated in a separate room.

We do not control air pressure nor the humidity level. As was shown repeatedly from monitoring of RV standards, the intra-run radial-velocity zero-point noise is on the order of 8 m s^{-1}, i.e. the stability during a run of several days to weeks. Longer-term season-to-season stability at this level has been difficult to achieve, especially in periods of very high ambient summer temperatures caused by Saharan dust or when access to the instrument is required for technical reasons.

The MED-RES fiber of the current bundle has been shown to be very susceptible to seeing variations, leading to up to 3 times poorer zero-point stability. We found that introducing a linear-motion fiber shaker at the telescope base can reduce this extra source of RV noise to just above the normal level achieved in steady seeing.

4.2 Modal noise

We investigated the presence of modal noise (e.g. Baudrand & Walker 2001), using flatfield spectra in the region of 500–

560 nm. We found that the main MED-RES fiber has a signal-to-noise (S/N) limit of 650, whereas the S/N limit of the HIGH-RES fiber is only 450. This while according to photon statistics a S/N level of 1100–1200 was expected for this particular test. The fiber shaker does not seem to make any improvement regarding the modal noise.

5 Efficiency

Some important contributing factors to photon losses are: seeing (for MED-RES and HIGH-RES modes 16 % loss at a seeing of 0.″8, 31 % at a seeing of 1.″0), the telescope and pickoff mirror (40 % loss), scattering in the 40 m long fibers, overfilling of the échelle grating (30 % loss), and only for the HIGH-RES mode the additional fiber-exit slit losses (40 % loss). For the LOW-RES and MED-RES modes of FIES we have consistently measured a total system efficiency (i.e. throughput), including the telescope and the atmosphere at zenith, of about 9 % in the V-band in good seeing conditions.

6 Target acquisition

For star-onto-fiber acquisition the target field is imaged onto 20″ field-of-view mirrors around the fibers. From the mirrors the beam is relayed onto the StanCam[2] direct imager, with a standard BVR filter set for fiber viewing. Visiting astronomers, who operate both the telescope and the instruments after initial instructions by staff, manage to put the target in the fiber in about 2–3 minutes after the telescope slew.

7 Data reduction: FIEStool

A purpose-built Python/IRAF[3] based data-reduction software package, called FIEStool[4], is in use at the telescope for quick viewing of the recently obtained data, for calibration-data master-frame reduction, and for quality control. FIEStool can be installed anywhere, to be used for final reduction at the home institute of the PIs. The final reduced FIEStool data products are provided in IRAF's order-by-order format, and in a general one-dimensional order-merged FITS format.

Although FIEStool was developed at NOT for reducing FIES spectra, it can also be used for data obtained with other fiber-fed spectrographs. For example, the South African Large Telescope (SALT) is currently implementing FIEStool for automated reduction of data obtained with their High Resolution Spectrograph (HRS).

[2] StanCam: http://www.not.iac.es/instruments/stancam/
[3] IRAF: http://iraf.noao.edu/
[4] http://www.not.iac.es/instruments/fies/fiestool/FIEStool.html

8 Use of FIES by the community

In just a few years after installation in a stable environment, FIES has become one of the work-horse instruments at the NOT. Over the last few years, FIES has been used on 30–40 % of all nights, either for partial or full nights. For 2012, FIES contributed to 37 publications in the regular refereed astronomical journals (with number count: A&A: 17, MNRAS: 9, ApJ: 6, Nature: 3, AJ: 2), out of a total of 104 such publications based on data obtained with the Nordic Optical Telescope that appeared in that year. See http://www.not.iac.es/news/publications/ for links to these publications.

Typical scientific programmes using FIES are: stellar abundances and atmospheric parameters $T_{\rm eff}$, $\log g$, and metallicity (e.g. Buchhave et al. 2012); radial-velocity studies of (suspected) binaries (e.g. Hansen et al. 2011) and planet hosts; stellar activity (e.g. Gondoin et al. 2012), line-profile variations, and seismology. In particular, FIES is much in use in support of space missions, for instance for target selection and follow-up of CoRoT/*Kepler* seismology and exoplanet studies (e.g. Deleuil et al. 2012; Gandolfi et al. 2013).

9 Planned and requested upgrades

We will upgrade FIES this year (2013), with a new slightly larger 2k×2k 15 μm pixel e2v CCD231-42 CCD allowing a wider wavelength range to be sampled (370–830 nm) with improved throughput in the red, and significantly less fringes. The new Copenhagen CCD3-controller will allow for 2–3 times faster readout, while keeping low read noise.

Furthermore, the NOT user community has requested upgrades to study magnetic stars through spectropolarimetry, and to study orbits of sub-Jupiter size exoplanets at a precision of about 2–3 m s^{-1}. Simultaneous sampling of the ordinary and extraordinary beams of the planned polarimetry unit will be possible using the two adjacent MED-RES fibers, in the wavelength range of 370–650 nm. To reach an RV precision of 2–3 m s^{-1} we need to redesign the fiber bundle, likely using octagonal fibers, and possibly introduce a double scrambler.

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