Precise Stellar Radial Velocities
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A new spectrograph dedicated to precise stellar radial velocities

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Abstract. The fiber-fed echelle spectrograph EMILIE designed for the measurement of stellar radial-velocity changes is presently being laboratory-tested. Using a 204 x 408 mm grating and a 1k x 1k CCD detector, it samples about 50% of the 410–620 nm wavelength range with spectral resolution $R \sim 150\,000$. This spectrograph is coupled to the telescope via a single 50-μm fiber, which accepts 2.7 arcsec from the sky. An automatic guiding system stabilizes the image at the entrance of the fiber. The fiber transmits alternately to the spectrograph the stellar beam and the reference beam. The same pixels of the CCD detector are used alternately for the two spectra, which requires an excellent short term stability. Hence, later on, the spectrograph will be located within a vacuum tank, with active thermal control. The instrument will be set up at the focus of the 1.52-m coudé telescope at the Observatoire de Haute-Provence (OHP) and will undertake programs of asteroseismology and detection of extrasolar-planets.

1. Introduction

Several spectrographs specialized in precise Doppler shift measurement presently reach accuracies between 3 and 10 m/s (Brown et al. 1994, Mayor and Queloz 1995, Butler et al. 1996). Two distinct calibration methods exist: 1) use of an absorption cell in front of the spectrograph to impress lines of constant wavelength on the incoming starlight, or 2) use of an optical-fiber feed for the starlight, with a second fiber carrying light from a stable wavelength source.

EMILIE is a new fiber-fed echelle spectrograph optimized for precise stellar radial velocity observations, which is being laboratory-tested. In the future, this spectrograph may be used, alone, or as a part of the Absolute Astronomical Accelerometry (AAA) project proposed by Connes (1985). A complete demonstration system has been built and laboratory-tested with encouraging results (Schmitt 1997).

Here, we present in Part 2 the optical layout of the EMILIE spectrograph. First laboratory results are exposed in Part 3. We briefly present in Part 4 a fast guiding system locked on the fiber input, intended to minimize the geometrical fluctuations of the stellar beam. This system has been recently tested at the 1.52-m telescope at the OHP.

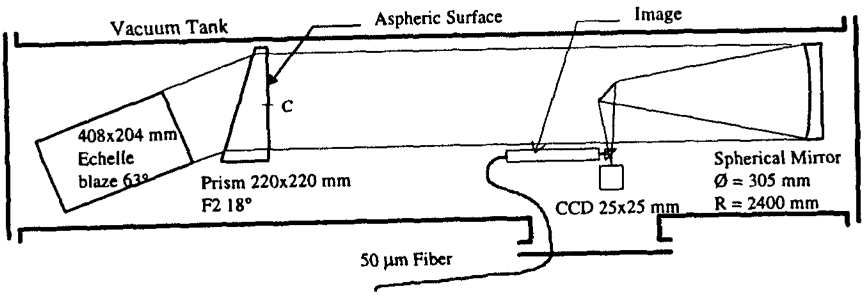

Figure 1. Schematic layout of EMILIE spectrograph optics.

2. Spectrograph design

The spectrograph is laid out in a Littrow-Schmidt configuration, shown in Fig. 1. Both spherical mirror and prism cross-disperser are used in double pass. The échelle is a Milton Roy grating with 31.6 grooves/mm, a 204 x 408 *mm* ruled area, blazed at 63°. The cross-dispersing prism, in F2 glass ($n_d = 1.62$ and $\nu_d = 36.37$), has been polished with a Schmidt profile to correct the spherical aberration of the collimator. The f/4 spherical mirror has a 305 mm diameter and the center of curvature C is at the center of the prism. The spectrograph is fed by a single 50-μm fiber through which an optical commutator alternately sends the stellar and reference beams. In this way both beams have the same optical path. Moreover, the elimination of the second set of images on the CCD allows us to use an image-slicer, which increases the overall efficiency. On the other hand, commutation between the beams requires very high short-term stability. No drift is permitted during the time interval between two exposures, i.e. 10–1000 s. Hence, we plan to install the spectrograph in a vacuum tank (10^{-2} mbar) with active thermal control. So far, EMILIE uses a 1024 x 1024 CCD detector with 24-μm pixels. The chip is cooled by a three-stage thermoelectric cooler with liquid circulation. The present CCD records 50% of the 410–620 nm wavelength range in 47 orders.

The spectrograph will be set-up at the Coudé focus of the 1.52 m telescope at OHP, using the guiding system described in Part 4.

3. First spectrograph laboratory results

All the surfaces have been controlled with a Fizeau interferometer. An overall check of the instrument with a Ne-He laser gives a spot size of about 6 μm which corresponds to an actual resolution of 800 000 while the theoretical diffraction-limited resolution is 1.2×10^6. With 24-μm pixels the pixel width is 1.5 km/s, and with a 24-μm input-slit width the wavelength-independent computed geometrical resolution is 200 000. This relatively high resolution gives two advantages: 1) fluctuations of the input beam due to incomplete scrambling (see Part 4) will

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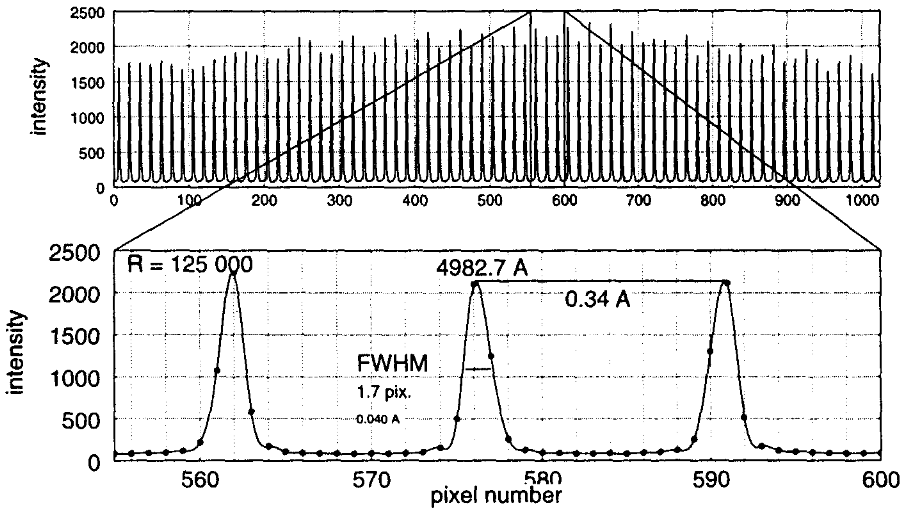

Figure 2. Spectrograph order 115. Fabry-Perot channelled spectrum from 4963.3 to 4993.2 Å. Lower curve results from a spline interpolation.

induce smaller wavelength shifts than in a lower resolution spectrograph, and 2) resolving the stellar photospheric line profile helps to detect intrinsic stellar effects.

Ray tracing showed that a field-flattening lens becomes necessary only for a larger CCD. To locate the position of the 47 orders, a high pressure xenon lamp was used. The beam was transported by a 50-μm fiber. The image-slicer not yet being available, a simple achromatic lens produced an input image of 25-μm diameter.

A channelled spectrum was obtained with a 3.7 mm FP interferometer; Fig. 2 shows one extracted order of this spectrum, which covers about 24 Å, and a zoom giving an estimate of the line-width, part of which is due to the FP itself.

The stability of EMILIE was next measured, with 5-cm thickness polystyrene shielding but without thermal control. Both the spectrometer and the Zerodur-spacer FP were at atmospheric pressure. Only four orders of the channelled FP spectrum were used, in order to speed up the sampling rate. We took a few hundred short exposures and computed the apparent velocity shifts relative to a reference spectrum taken at the beginning of the night. We see, in Fig. 3, a slow drift of few hundred m/s due to spectrometer mechanical relaxations and temperature changes, FP drift being negligible. Next, our data were treated to simulate the use of a stable-wavelength reference spectrum alternating with the spectrum under test: the difference between each even-exposure and the average of the two odd-exposures on either side was calculated. The results, in Fig. 3, show the present performance. We think that the residuals (with 1.3 m/s RMS) are mostly due to temperature instabilities inducing air-convection inside the

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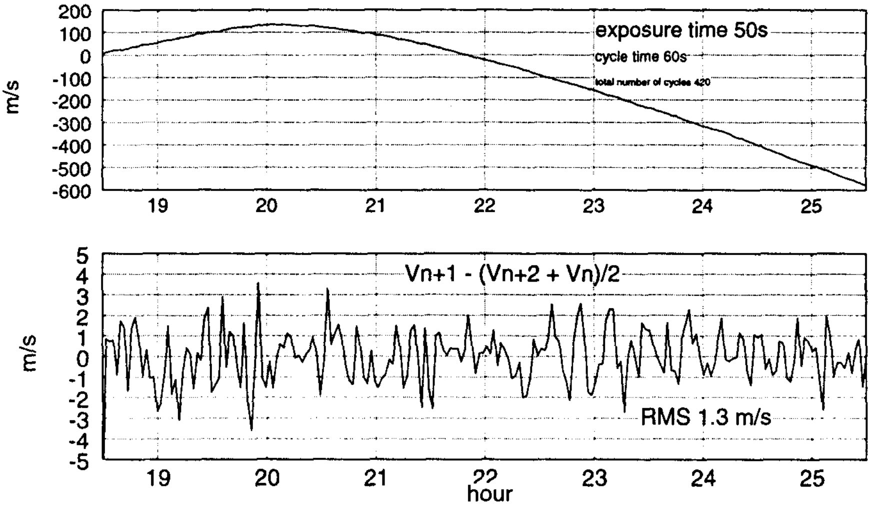

Figure 3. Spurious spectrometer velocity shifts obtained with FP spectrum during 7 hours run. Upper curve gives overall drift, and lower curve the "fast" fluctuations which limit accuracy when star and reference are used alternately.

spectrograph. We hope that these artefacts will be much reduced in the vacuum tank with active temperature control.

4. Guiding system locked on the fiber input

The well known scrambling action of a step-index multi-mode fiber does not completely eliminate the effect of spatial fluctuations of the stellar beam. The residuals are critical in cases when the goal is 1 m/s precision, since fluctuations in the near- or far-fields of a fiber feeding a spectrograph introduce wavelength shifts. These are presently the major source of RV errors, at least with the ELODIE spectrograph at OHP (Connes et al. 1996).

Telescopes degrade the image further because they have tracking errors and shake in the wind. Slow drive-error oscillations of a few arcsec are easily removed by classic offset guiding. On the other hand, telescopes have smaller but faster oscillations at their natural frequencies (between 1 and 10 Hz) especially in windy conditions. The telescope itself cannot be guided faster than its own natural frequencies, and the only practical solution is to guide a low-inertia component faster than the telescope resonances. The classic system consists of a CCD detector, a computer-based control system, and a small tip-tilt mirror located in a pupil-image plane. Such systems have a drawback: the star image position-detector is independent of the fiber input, and one may fear slow drifts in their

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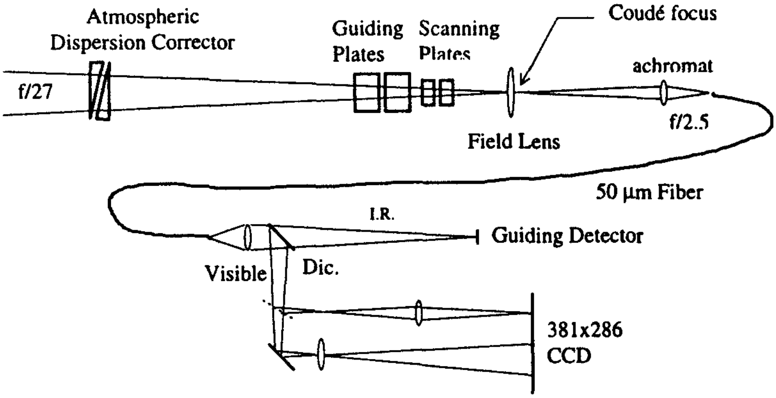

Figure 4. Layout of automatic guiding and focusing system locked on fiber input. Dimensions are 5x5x5 mm and 10x10x20 mm for the scanning and guiding plates respectively.

relative positions. This point is important especially for long-term programs like extrasolar planetary searching.

The principle of our system, shown in Fig. 4, is as follows: the f/27 beam of the telescope (at the coudé focus) is converted to f/2.55, and the star image is formed on the fiber entrance which accepts 2.7 arcsec on the sky. The fiber input itself plays the role of position detector. A pair of plane-parallel "scanning" plates introduces two small oscillations of the image in two perpendicular directions X and Y, with frequencies f_1 and f_2 in the 1 to 2 kHz range. A small translation of a lens along its axis produces a Z translation of the image, hence a focusing error, with frequency f_3. At the output of the fiber, an intensity detector (of any type) followed by three synchronous demodulators at frequencies f_1, f_2 and f_3 reconstitutes three error signals SX, SY and SZ. SX and SY are applied to two "guiding" plates, at closed-loop frequencies up to 50 Hz. SZ may be applied either to the Z-lens, or to the telescope secondary-mirror driving-motor, or to both in parallel. For detectors, we have used PIN and avalanche Si diodes, which receive only the NIR part of the beam. The visible part is split-off and produces images of the near- and far-field side-by-side on a CCD. Later on, this same beam will be sent to the spectrograph.

During a star test of our guiding system, we made long sequences of short exposures (60 s) to estimate the geometrical changes of the two fields. We computed on-line the XY shifts of the photocenter and the drift of the first order momentum for both images, relative to the beginning-of-night reference. We used alternately our automatic guiding system, and manual guiding with the help of a video screen (which roughly simulates CCD guiding). Fluctuations of photocenter and momentum decrease with automatic guiding on, but do not vanish. Under average OHP-seeing conditions (about 2 arcsec), fast fluctuations of the photocenter of the near-field are about 15 nm RMS, with a 50-μm core fiber.

With EMILIE at the output of the same fiber, these fluctuations would induce about 0.45 m/s RMS error. The effect of the fluctuations of the momentum, and of the far-field are difficult to predict in m/s but will certainly be larger. However, our system is fully compatible with the use of a double-scrambler (Hunter and Ramsey 1992).

5. Conclusion

We hope to reduce systematic errors through having the spectrograph in a vacuum, the use of a single fiber and our dedicated guiding system (to be fully described elsewhere). We intend to finish the laboratory-tests of the spectrograph, to put it in a vacuum, and to set it up at the 1.52-m telescope. Next, we should begin programs of asteroseismology and detection of extrasolar planets.

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Discussion

Fischer: You are correcting the image position at approximately 50 Hz. Could you correct at a lower frequency? How have you quantified the frequency?

Bouchy: Our guiding system corrects all frequencies up to 50 Hz. The power spectrum of the positions of the guiding plates indicate that their responses decrease rapidly beyond 50 Hz.

Hearnshaw: Why did you choose a pressure of 10^{-2} mbar for the vacuum tank? Does it have to be that low, or would 1 mbar suffice?

Bouchy: Our vacuum system allows us to reach 10^{-2} mbar, so why shouldn't we profit from it?

Latham: There are some interesting features to this instrument, and the results of the laboratory tests are promising. What limiting magnitude do you expect to reach at 1 m/s?

Bouchy: Our program will be dedicated to bright stars. We will probably be limited to magnitude 8.

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