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Ondřejov Echelle Spectrograph – OES

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This paper describes the OES echelle spectrograph, a new coudé focus instrument of the 2 m telescope at Ondřejov Observatory. The design, optical scheme, and mechanical solutions are presented. A brief review of laboratory tests is given, too.

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1 Introduction

Since its very beginning, the observational programme of the 2 meter telescope at Ondřejov has been oriented to high dispersion spectroscopy. The primary instrument was a spectrograph in the coudé focus. Originally, the three cameras designed for photographic plates as light detectors were able to produce spectra with reciprocal dispersion from 34 to 4 Å/mm. When the electronic detectors started to be available, the two cameras with longer focus (700 and 1400 mm) were adapted to carry dewars with CCD's. This solution was not possible for the shortest camera (f=350 mm). Later, a lens objective with focal length 400 mm was designed and built. Thus, the coudé spectrograph in the "electronic era" is able to offer spectra with the same spectral resolution as before but much better signal-to-noise ratio. The only disadvantage of such a spectrograph equipped with electronic detectors is the limited spectral region. The most straightforward solution of this problem is to build an echelle spectrograph. Hence the motive for the project called OES (**O**ndřejov **E**chelle **S**pectrograph).

The practical points which influenced the design of the OES were as follows:

- the experience with fiber fed HEROS spectrograph at Ondřejov
- the limited space of the coudé room where the original spectrograph was installed
- the availability of the second coudé room
- the possibility to switch from the echelle spectrograph to the "classical" coudé and vice versa within a night.

The HEROS spectrograph (Kaufer 1998, Šlechta and Škoda 2002) was temporarily attached to the Cassegrain focus of the 2 m telescope in 2000 – 2003. Though more than 1500 stellar spectra were obtained, problems in merging of orders (manifested by a variable wave-like structure of the stellar continuum even after flatfielding) persisted through the operation of the spectrograph at Ondřejov. Many tests were performed (Škoda and Šlechta 2002), but a reliable general rule how to overcome this difficulty has never been derived. More, the fixed diameter of the fiber lead to very low efficiency of the spectrograph in the case of bad seeing, quite frequent at Ondřejov in the winter time. Thus, the HEROS experience called for building an echelle spectrograph in coudé room fed by the available mirror train.

The actual coudé spectrograph is placed in the room (called coudé room No.1) on the east side of the polar axis. Most of its functions are computer controlled and/or displayed – in addition to the CCD controller, also spectrograph configuration, calibration lights, camera focusing, exposure meter, grating angle, filters, height of the slit, guiding camera, and camera shutter. For details see Honsa and Šlechta (2002). Thus, it seemed most natural to place the planned echelle spectrograph in the same room.

Very soon we realized that the building and testing of a new coudé instrument would seriously complicate the operation of the actual coudé spectrograph. It was than decided to build the echelle spectrograph as an independent instrument in the coudé room No. 2 on the west side of the polar axis. This solution assumes that most of the auxiliary units of spectrograph will be common to both instruments, and it supports the idea to readily switch between coudé rooms Nos. 1 and 2. This option could enhance the efficiency of the coudé focus. In the period of poor seeing or bad transparency a low dispersion mode in the "classical" coudé can be used, while in excellent conditions it would be possible to use the high dispersion of the OES spectrograph.

2 Instrument design

The OES spectrograph is designed as a "white-pupil" echelle spectrograph, a solution which keeps the size of the crossdisperser and the camera aperture diameter in technically feasible relations. Similar solution was used in the case of ELODIE (Baranne et al. 1996), TLS–Echelle Spectrograph or FEROS. For details see the web pages:
`www.tls-tautenburg.de/coude/echelle-spectrograph.html`,
`www.ls.eso.org/lasilla/sciops/2p2/E1p5M/FEROS`

2.1 The optical scheme

The spectrograph is fed by a coudé train using three flat mirrors. An f/32 collimator **B** (focal length of 4637 mm) produces a beam of 142 mm in diameter (taking in account the effective grating length of 408 mm). The echelle grating **C** used has a $\tan\theta$=2.6 (θ=69°) blaze angle. It is the most valuable optical component (420 x 165 x 74 mm with 54.5 g.mm^{-1}) manufactured by Milton Roy. Among the gratings offered we choose one with large θ, and lower number of orders to avoid numerous order connections.

The first intermediate spectrum is imaged with an f/3.6 parabolic mirror **D** (focal length of 1628 mm), sometimes called camera mirror, after the reflexion on a small flat mirror **E** very close to the grating. An f/3.1 parabolic secondary collimator **F** (focal length of 1086 mm) then forms a "white pupil" in parallel light. This pupil is the white image of the echelle grating (diameter 142 mm) but reduced to a diameter of 95 mm. The dispersion crossing is done by a 54.5° LF5 prism **G** placed in front of a CANON EF 200 f/1.8 camera lens **H** (f=200 mm). In Table I, 42 orders covering the spectral range from 3870 Å to 7130 Å are listed.

These orders are then recorded on an EEV 2048 x 2048 array **I** with 13.5μm pixels. It is a commercially available Versarray 2048B system produced by Roper Scientific. The system includes a dewar and a controller. The order distance is 12 pixels in the red end, 27 pixels in the blue end of the spectrum. The linear reciprocal dispersion is 2.4 Å/mm at 5000 Å. If the slit width is set to 600 μm (2 arcsec in the coudé focus of the telescope), width of its image is 40 μm in the camera, i.e. resolution is 51600 at 5000 Å; the

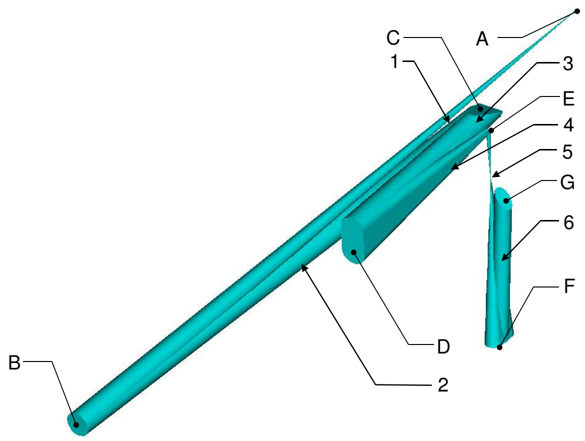

Fig. 1 Optical layout and perspective view of OES. Numbers and letters correspond to beams and optical/mechanical elements described in text.

"two-pixel" resolution is 77000. Starting at 4500 Å uncovered gaps in the spectrum between neighbouring orders start to appear. However note that the important lines of hydrogen and helium are covered well, (see Table I). As most of the imaging optical elements of the OES are mirrors (Canon lens being the only exception), the axis of optical beams cannot be placed in a single plane. The optical layout and perspective view of OES is presented in Fig. 1.

A flat deflection mirror in the polar axis (which lays in the vertical plane (XY) sends the light to the slit **A** placed in the focus of the collimator **B**. The axis of that beam (1) is inclined by 2.6° to the horizontal plane (XZ) and lays in the second vertical plane (YZ). The origin of the coordinate system used – O – is defined as a point where the polar axis crosses the deflection mirror. The axis of the beam(2), from the collimator to the grating **C**, is horizontal, i.e. parallel with the YZ plane. The axis of the beam(3) (mean wavelength – 4800 Å), from the grating to parabolic mirror **D**, remains horizontal, but is inclined by 5.5° to the vertical plane (YZ). The axis of the beam(4), from the parabolic mirror to the small flat mirror **E**, is again horizontal, but inclined to the vertical plane (YZ) by 1.3°. The axis of the beam(5), from the small flat mirror to the secondary collimator **F**, is vertical. The axis of the beam(6), from the secondary collimator to the crossdisperser **G**, lays in a vertical plane parallel with plane (XY) and is inclined to the vertical by 4.8°. Finally, the axis of the beam(7), from the prism to the Canon lens (not shown in Fig. 1) is in a vertical plane parallel with (XY) plane and inclined by 43.4° to a vertical plane parallel with (YZ) plane (mean wavelength – 4800 Å).

The described optical arrangement was chosen in order to keep the efficiency of the grating high. When

Table I. OES wavelength coverage

Order number	Start (Å)	Centre (Å)	End (Å)
91	3870	3895.6	3919
90	3913	3938.9	3962
89	3957	3983.2	4007
88	4001	4028.4	4053
87	4048	4074.7	4099
86	4095	4122.1	4147
85	4143	4170.6	4196
84	4192	4220.3	4246
83	4243	4271.1	4297
82	4295	4323.2	4349
81	4347	4376.6	4403
80	4402	4431.3	4458
79	4457	4487.4	4515
78	4514	4544.9	4572
77	4573	4603.9	4632
76	4633	4664.5	4693
75	4695	4726.7	4755
74	4758	4790.6	4820
73	4824	4856.2	4886
72	4890	4923.6	4954
71	4960	4993.0	5023
70	5030	5064.3	5095
69	5104	5137.7	5169
68	5178	5213.3	5245
67	5255	5291.1	5323
66	5336	5371.2	5404
65	5417	5453.9	5487
64	5502	5539.1	5573
63	5590	5627.0	5661
62	5679	5717.8	5753
61	5772	5811.5	5847
60	5869	5908.4	5945
59	5968	6008.5	6045
58	6071	6112.1	6149
57	6178	6219.3	6257
56	6287	6330.4	6369
55	6402	6445.5	6485
54	6520	6564.9	6605
53	6643	6688.7	6730
52	6772	6817.3	6859
51	6905	6951.0	6994
50	7042	7090.0	7134

the incoming and dispersed beams lay in grating normal plane, there has to be an angle between them which takes in account the configuration od mirrors. Efficiency then decreases. Our choice was to use beams inclined to the normal plane by γ=2.76°, this angle being dictated by the demands of mechanical construction. The grating equation is modified to

$$\sin\alpha + \sin\beta = K \times \lambda / \cos\gamma.$$

The entrance slit then can be opened most widely for a given resolution. However, in this case the spectral lines are not perpendicular to the direction of dispersion, and are inclined by 14° in the bluest orders and by 12° in the reddest one. The angle was confirmed by the exposures of Th-Ar spectrum in the first intermediate focus of the **D** mirror. See Fig. 10. To eliminate this line inclination, it would be possible to rotate the entrance slit. Since the expected length of line image is only several pixels, the remaining diferencial inclination should have no effect on the line position. Or, the inclination can be corrected by software: when the order images are linearized, the pixel rows can be shifted accordingly.

2.2 The mechanical solution

The spectrograph is mounted on two steel tables $\mathcal{A}$ and $\mathcal{B}$ (Fig. 2) that sit on the concrete ground, which is in fact part of the telescope pier. A three point support is provided for each table. The slit head is on a bench outside the coudé room No. 2. It is fixed to the telesope pier and covered by a light-tight box. The light entering the box from the polar axis and leaving the box to the spectrograph is protected by a light-tight tube.

Table $\mathcal{B}$ carries the collimator **B** (Fig. 3) enclosed in a frame, which can be coarsely adjusted in all three axis. Fine adjustment is realized by rotation of the mount of the mirror around vertical and horizontal axis.

Much heavier table $\mathcal{A}$ consists of four modules manufactured from steel profiles. They are welded from profiles with hollow square cross-section supported by oblique bars. This solution ensures very good stiffness of the structure. Table $\mathcal{A}$ carries four independent frames which create mechanisms for aligning the grating **C** (Fig. 4), parabolic mirror **D** (Fig. 5), parabolic mirror **F** (Fig. 7) and the detector train (Fig. 8) consisting of prism **G**, lens **H** and CCD detector **I** (Fig. 9). The four frames as well as the collimator frame are assembled from alluminium profiles of the ITEM building kit system. The three frames carrying grating and two parabolic mirrors use the same system as the collimator **B** – coarse adjustment in all three axis, while fine adjustment is realized by rotation around two perpendicular axis. In the case of the grating one uses flexible backlash-free elements. Each component on the frame carrying the detector train has his own mechanism for adjustment. The mount of the prism allows to set up the incidence angle of the beam(6) – together with the movements of the collimator **F**. The position of the Canon lens can be coarsely adjusted in three axis, while the mount of the detector dewar can be rotated around axis perpendicular to the axis of the beam(7). The focusing is done by a step motor in axial direction.

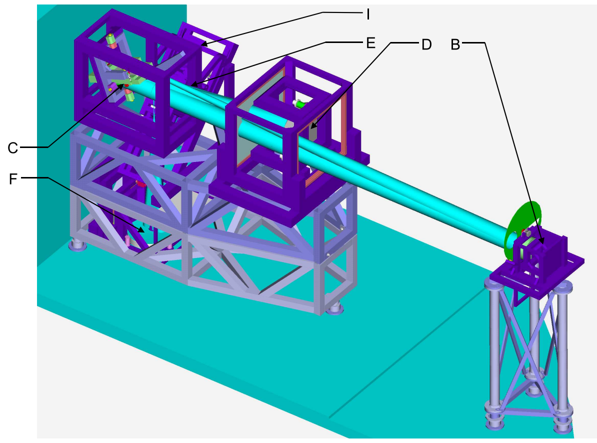

Fig. 2 Tables $\mathcal{A}$ and $\mathcal{B}$ with the mounts of main optical elements.In the middle is the parabolic mirror **D**, on the right side the module of the collimator **B**. On the left is the grating **C** and the detector train. In the bottom is the module of the secondary collimator **F**. Visible are also beams (1), (2), (3), and partly (6)

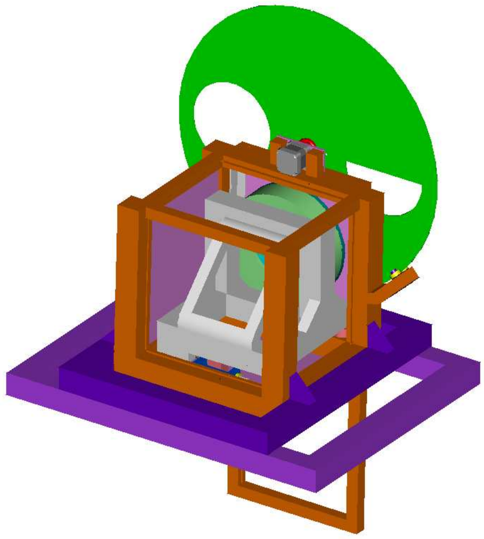

Fig. 3 Mount of the collimator **B** with a circular rotating disk serving as shutter and Foucault diafragm for focusing procedure

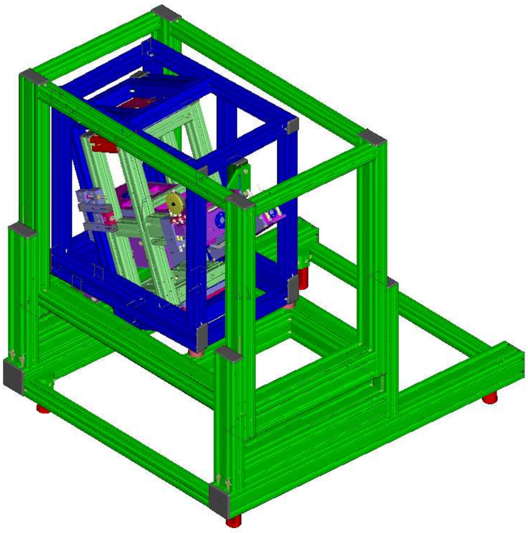

Fig. 4 The mount of the grating

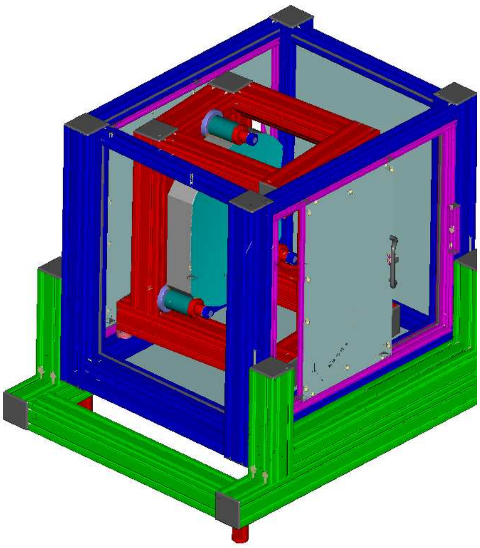

Fig. 5 The mount of the camera mirror **D**

2.3 The calibration lights

The calibration lamp assembly (CLA), common to both coudé instruments as mentioned above, consists of a hollow cathode lamp (argon, thorium), and a quartz tungsten halogen lamp for internal flat field exposures. A fold mirror carriage in the polar axis enables two optical paths. In the first position, the fold mirror alows the stellar light to enter the coudé system. In the second carriage position, the fold mirror directs the calibration light from CLA to the spectrographs. The light from both lamps first enters a beam splitter, which is nearly transparent for arc lamp and reflects about four percent of flat field lamp. The light of calibration lamps illuminates diffusing glass plates and then is focused by a simple optical system. Another fold mirror carriage sits bellow the CLA mirror. The second carriage has three ports, which enables three different paths. In the first position, the light

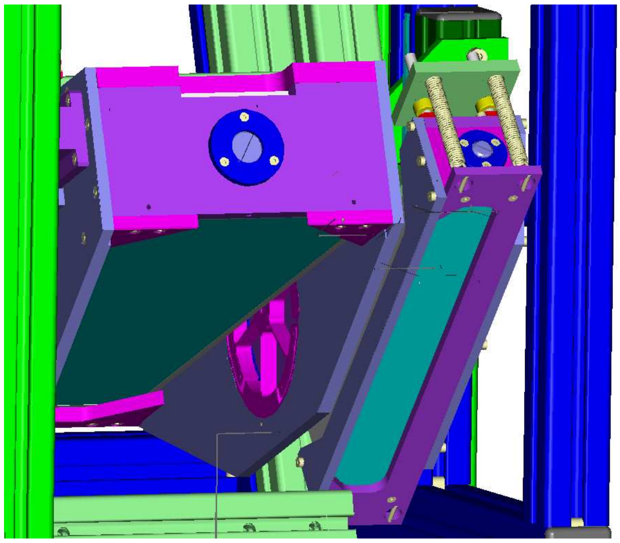

Fig. 6 The mount of the small flat mirror **E** (right), grating **C** on the left side

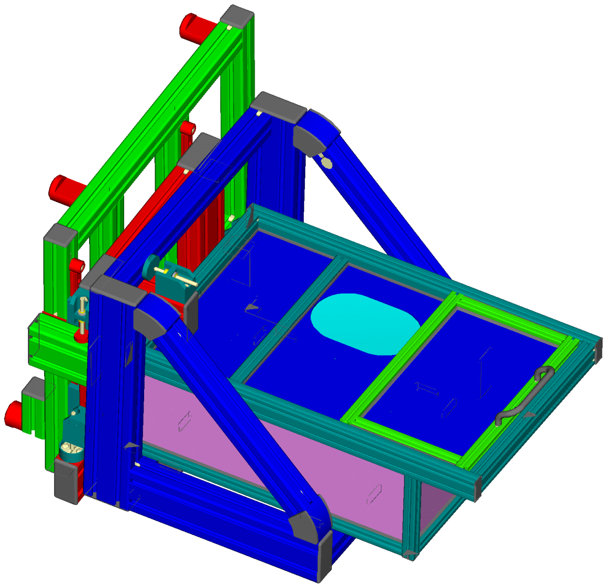

Fig. 7 The mount of the secondary collimator **F**. The aperture in the buffle in front of the mirror corresponds to the shape of incoming and outcoming beams

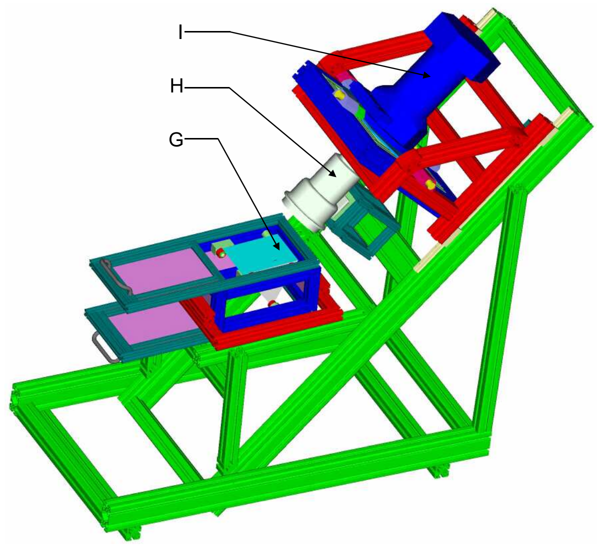

Fig. 8 The mount of the detector train. Letters denote the particular elements as described in text

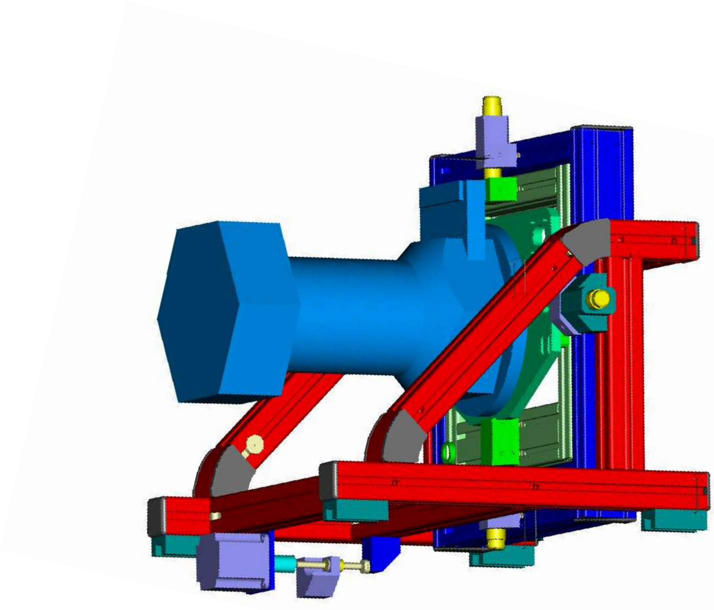

Fig. 9 The mount of the detector dewar. The step motor is in the bottom on the left side

is directed to the OES, in the second, light continues to the original coudé system, and the third position blocks the light from the polar axis and enables a laser beam to enter OES for adjustment purposes.

2.4 The slit viewing camera

The light of the star is reflected from the slit in the condition of total reflection and displayed on the monitor of the camera – intensified TV camera EEV CCD 65 already used with the former coudé spectrograph. A cross on the monitor indicates the position of the perpendicular secondary slit, which defines the slit height. The optimal position of the star image can be checked by the reading of the exposure meter. A 5-position filter wheel in front of the camera controls the optimum stellar image on the monitor.

2.5 The exposure meter

The light for the exposure meter is deflected by a semitransparent flat mirror (about 5 percent of the incoming light) behind the slit. The light is detected by a Hamamatsu Photon Counting Head H 7155-21. Similar exposure meter is used in the former coudé spectrograph.

2.6 The instrument control

A new system for aquisition of astronomical spectra was developed for the controller of the EEV CCD chip. This code, called PESO, written in Python also controls the basic function of the spectrograph (Škoda et al. 2005):

- Foucault diafragm in front of the collimator **B**
- focusing step motor of the CCD dewar on the detector frame
- exposure of the calibration lights (positioning of the flat mirror, on/off of the lamps)
- shutter in front of the detector dewar
- filters of the slit-viewing camera

2.7 The spectrograph enclosure

The enclosure for the OES spectrograph is located in the coudé room No. 2. It was designed and built specially for that instrument and it should maintain a steady, controlled environment around the spectrograph. Also the enclosure should keep the level of parasit light on the lowest possible level. The spectrograph enclosure is a wood structure with double-door entry way. The interior is coated with flat black paint. A simple air conditioner and air purifier are also installed in the room. The enclosure should be kept closed, the only reason to entry during the routine operation is to refill liquid nitrogen in the dewar.

3 Current status and future work

Designs for all mechanical and optical structures of the spectrograph OES have been finalized and shopwork was completed for collimator **B** unit, both table

$\mathcal{B}$ and the spherical mirror. Table $\mathcal{A}$ was completed and definitely installed in the coudé room No.2. The frame of the grating **C** was assembled and put on the table $\mathcal{A}$. The same status pertains mirror **D**. The components **A** (entrance slit), **B**, **C** and **D** were adjusted and a verification test of their basic functionality was performed. An auxiliary mirror (substituting the mirror **E**) was placed near the grating and a small TV camera in the first intermediate focus of the spectrograph recorded a filter isolated Th-Ar spectrum. It is presented in Fig. 10. The cause of the line inclination and the possible treatments are explained in subsection 2.1.

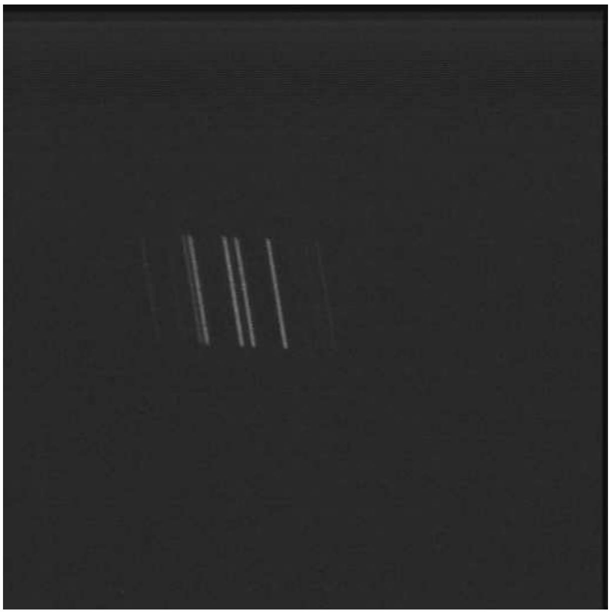

Fig. 10 A group of comparison lines in the first intermediate focus. The cause of the line inclination is explained in text

The shop work of the small flat mirror **E** is nearing completion. In the coming weeks, the mounting of mirror **F** will be completed and installed on the table $\mathcal{B}$. A second test of the basic functionality will proceed in order to check the off-axis effects. The detector train is to be completed late in the summer 2005 and than a period of on-sky testing will commence.

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