Serb. Astron. J. № 171 (2005), 55 - 63
DOI: 10.2298/SAJ0571055V

UDC 520.84 : 520.353
Professional paper

CHARACTERISTICS OF THE BELGRADE ASTRONOMICAL OBSERVATORY'S STELLAR SPECTROGRAPH

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(Received: November 4, 2005; Accepted: November 7, 2005)

SUMMARY: In this paper the main features of the new SpectraPro-750 spectrograph of Belgrade Astronomical Observatory are described. The instrumental profile of the spectrograph for the 1200 l/mm grating is determined using a fiber optic bundle with fibers arranged in a pseudo-slit pattern. This instrumental profile is compared to the instrumental profiles obtained when the same fiber optic bundle illuminates the entrance slit with different widths. From appropriate instrumental profiles the practical spectral purities and the spectral resolutions for different entrance slit widths are obtained. The variation of the reciprocal linear dispersion with wavelength in the spectral range 350 - 600 nm is determined. A proposal for a link between telescope and the spectrograph is given.

Key words. Instrumentation: spectrographs

1. INTRODUCTION

SpectraPro-750 is the new fiber-fed spectrograph intended for use primarily at the new 60 cm Cassegrain telescope. The primary focal length of the telescope is 1.8 m (focal ratio f:3). The system focal lengths are 6 m (focal ratio f:10) and 2.5 m with reducer (focal ratio f:4.2), respectively. The optical setup of telescope-spectrograph link will be adapted to this telescope. Due to its technical and mechanical characteristics the spectrograph is relatively easy to transport, enabling its use at other telescopes as well. Consequently, the optical link between spectrograph and telescope has to be flexible. The spectrograph has been planed for the recording of low-resolution spectra of relatively faint stars and asteroids, medium-resolution spectra of relatively bright stars and studies of the variations in highly broadened spectral line profiles. It is suitable both for determination of gas movements in circumstellar disks as well as for radial velocity measurements of close binary stars, where velocities of several hundred km/s are often observed.

In this paper we present the main characteristics of this instrument, its supplement accessories, instrumental profile and the results of experimentally obtained reciprocal linear dispersion in the spectral range 350 to 600 nm.

2. EXPERIMENTAL SETUP

The experimental layout is shown in Fig. 1. The SpectraPro spectrograph is equipped with two active ports: the entrance and the exit port. At entrance port there is a permanent adjustable entrance slit and an imaging fiber adapter. The exit port with a detector adapter permits the mounting of a CCD camera. The CCD camera is controlled by the ST-133A Controller. A fiber optic bundle allows the spectrograph to be fed by light from a spectral calibration lamp. The operation of spectrograph and the CCD camera is controlled by a computer using the WinSpec/32 software package for spectroscopy.

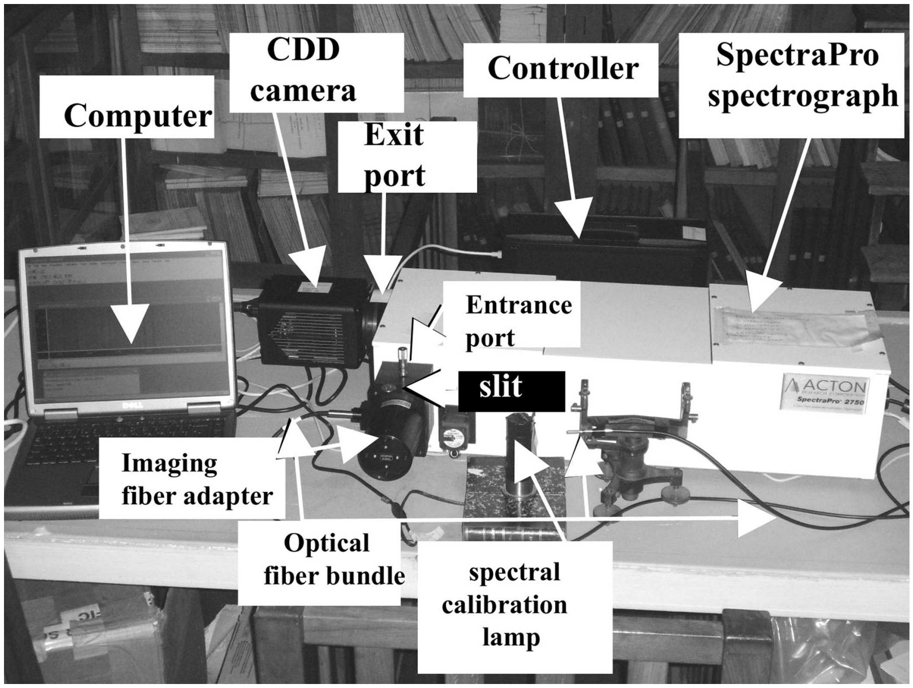

Fig. 1. *Experimental setup.*

2.1. The spectrograph

The new SpectraPro-750, model 2750 of the Belgrade Astronomical Observatory, manufactured by Acton Research Co. is of Czerny-Turner type. It is intended for spectral recording and analysis in spectral regions from violet to infrared. The spectrograph is image corrected and optimized for CCD spectroscopy. The spectrograph aperture ratio is f:9.7. The focal lengths of the aspheric collimator and camera mirrors (Fig. 2) are 750 mm. The camera focal plane is 27 mm wide and 14 mm high.

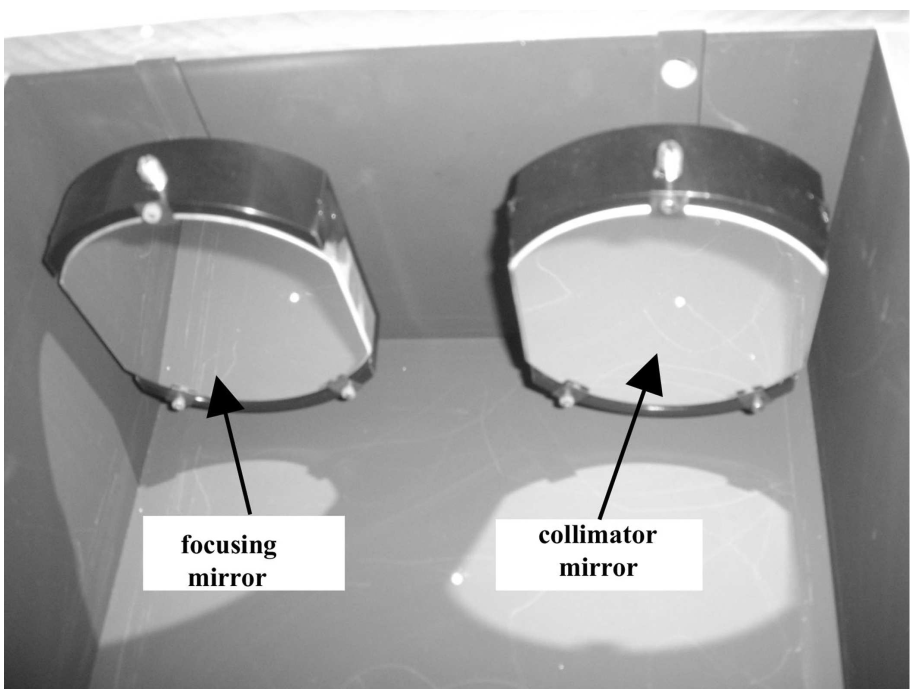

Fig. 2. *Collimator (right) and focusing mirror (left).*

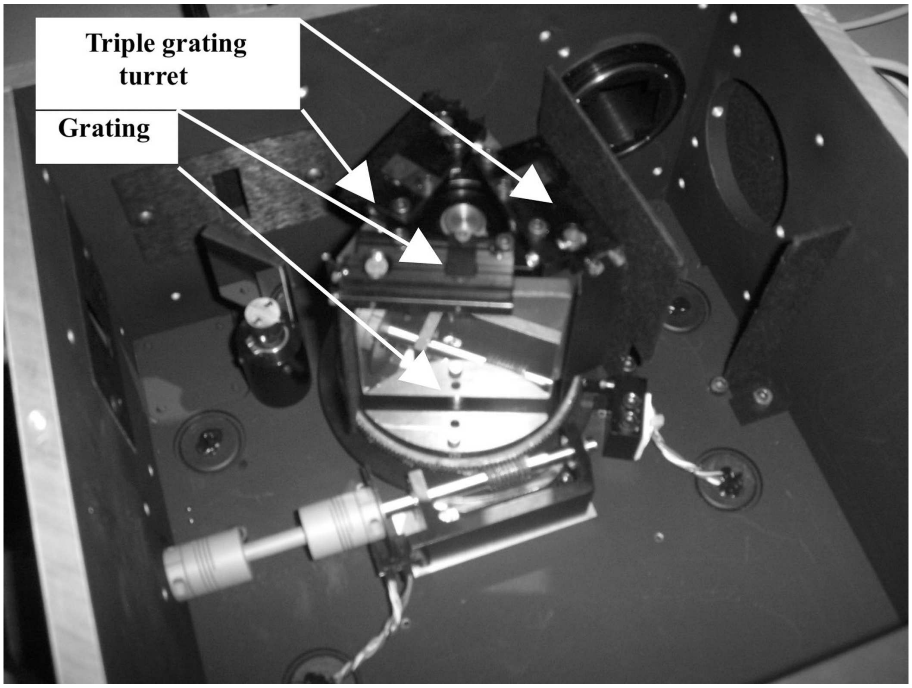

Fig. 3. *Triple grating turret.*

The spectrograph is equipped with three 68x68 mm^2 ruled diffraction gratings: 300 l/mm, 600 l/mm and 1200 l/mm, all blazed at 500 nm. These gratings are mounted on an indexable triple grating turret (Fig. 3). The advantage of having a multiple-grating turret is that the dispersion and spectral resolution can be matched to different requirement trough grating interchange. Grating positioning is controlled by a microprocessor through a stepper motor, enabling accurate wavelength selection. The entrance slit is 14 mm high and its width is micrometer adjustable up to 3 mm. The micrometer knob is graduated in 10 μm divisions. Each revolution increases the slit width by 250 μm.

2.2. Fiber optics

Light from observed objects in the telescope focal plane is collected by fiber optics and fed into the spectrograph. The spectrograph is provided with two optical fiber bundles: single- and four-leg fiber bundles (Roper Scientific ARC SpectraPro Serie). The optical fibers are arranged in a close-packed bundle. Inputs have a circular arrangement, whereas at output the fibers are reformatted into one-dimensional fiber arrays (pseudo-slit or shortly: slit). The fiber bundle transmission is higher than 35% /m in the spectral range from 190 nm to 1100 nm. Maximum transmission is about 46%/m at about 800 nm.

The single-leg bundle contains 19 fibers. The pseudo-slit is 4.6 mm long and 200 μm (about 245 μm diameter with cladding) wide. This UV-VIS fiber optic bundle (LG-455-020-3) is 3 m long and suitable for measurements in the spectral range 400 - 2200 nm.

The size of the stellar image depends on the optical quality of the sky, i.e. on the so-called seeing. When the exposure time (integration) is long compared to the atmospheric coherence time, the image of a point source (stellar image for example) will be smeared over the focal plane. The angular diameter of this stellar image at geographical sites with good astronomical atmospheric conditions is about $1''$ (seeing angle). The linear size of the image depends on the telescope focal length. At a telescope focal length of 6 m, the $1''$ image size will be about 30 μm (12 μm with reducer). At a site with much worse seeing, the image size is much larger (for example by a factor 5, i.e. 150 μm). On the other hand, the single-leg fiber bundle-input consists of 19 fibers. The central fiber is surrounded by six fibers, and the outer circle contains 12 fibers. The diameter of one fiber is 200 μm, and the diameter of the bundle is 1000 μm. Thus, the image even at poor seeing (let say 100 μm) will cover a relatively small area of the input pupil bundle.

The four-leg bundle contains four groups of fiber bundles as input. The input consists of three fibers arranged in a circular input-diaphragm. The output has four pseudo-slits with three 200 μm diameter fibers (about 245 μm diameter with cladding) per slit and about 1 mm spacing between slits. The distance between the ends of the first and fourth slit is about 5.9 mm. This bundle (model QFB-455-3) is 1 m long and operates well in the spectral range 190 -1100 nm.

For imaging of the fiber bundle slits on the spectrograph entrance slit there is an imaging adapter (model FC-446-030). It consists of two mir-

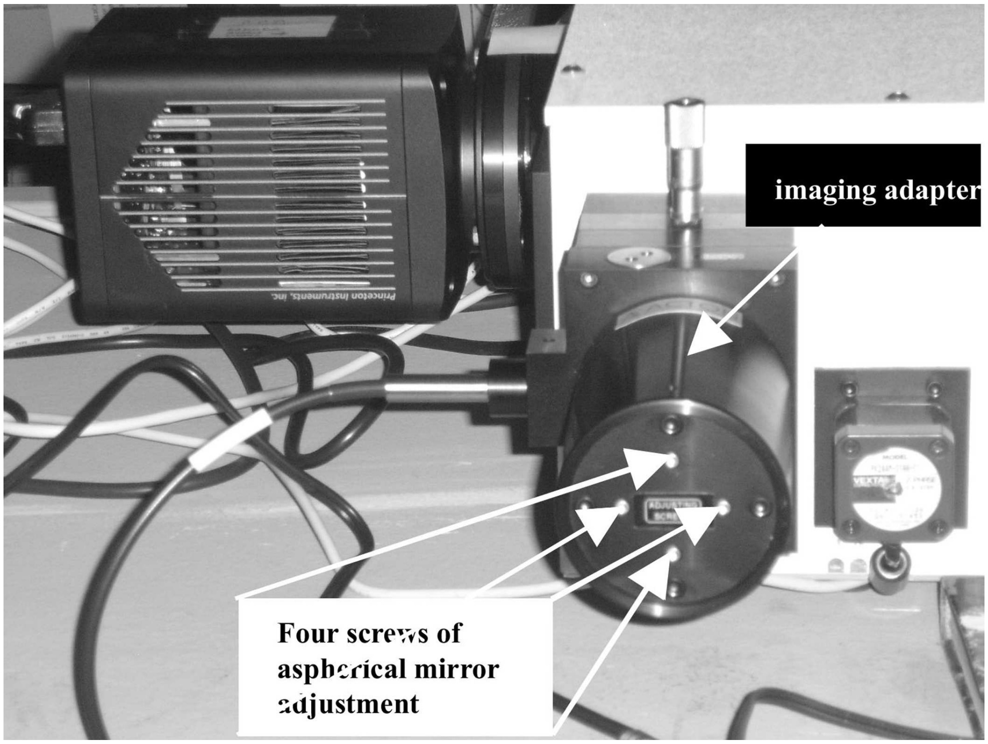

Fig. 4. *Imaging adapter: four screws for mirror adjustment.*

rors: a flat-mirror and an aspheric mirror. This optical design eliminates the chromatic aberration and astigmatism. The aspheric mirror is adjustable (by means of the four screws, Fig. 4.), allowing precise positioning of the fiber bundle image on the spectrograph entrance slit.

2.3. Detector system

The detector system is a Spec-10 (Princeton Instruments) detector, optimized for spectroscopic applications. It consists of a CCD camera head (type Spec-10:256/TEPLUS-A) and a controller. The CCD camera head contains a CCD array, cooling system and electronics. The CCD is a Marconi CCD Scientific Grade 1 rectangular front illuminated MMP CCD chip. The active pixel format is 1024x256-squared pixels of 26x26 μm^2 in size. It allows an image area of 25.6x6.7 mm^2. The spectral range covered by a single CCD image depends on the reciprocal linear dispersion. A range of about 26 nm is covered in the first order visible region with the 1200 l/mm grating. A forced air multi-staged Peltier thermo-electric cooler cools the chip. The temperature can be set in the range +20 °C to −75 °C and stabilized down to −70 °C. Upon reaching the set temperature the control electronics stabilizes it to within 0.05°C. The maximum quantum efficiency in the visual part of the spectrum is about 48% (peaked at about 630 nm). The full well capacity of the pixels is 500000 electrons. The dark current is 0.8 electrons/px/s.

2.4. Spectral calibration lamp

The spectral calibration lamp is a pencil-shaped discharge lamp containing argon and mercury Hg(Ar) (ORIEL Instruments, model 6035). The lamp produces narrow and intense lines from UV (starting at ∼185 nm) to IR (ending at ∼1710 nm), suitable for wavelength calibration, through excitation of mercury atoms in the ambient argon gas. The lamp is temperature independent producing the same lines at different temperatures. The average intensity is constant and reproducible. In comparison with other lamps it has a long lifetime (about 5000 hours). The lamp is operated by an AC power supply (model 6048).

2.5. Software

The CCD camera and the spectrograph are controlled by the software package WinSpec/32. This 32 bit Windows software package for spectroscopy provides spectral acquisition, data processing, display and archive. Fig. 5 illustrates the main WinSpec/32 window that consists of title bar, menu bar, snap-in tool bar and custom tool bar. In the main display the spectrum of the Hg(Ar) lamp is shown (two spectral lines of mercury are visible near 580 nm). The intensity distributions along the dispersion axis and perpendicular to it at cursor position are presented at the bottom and left-hand side of the spectrum. In the lower left part of the display the information box is visible. In this box the main

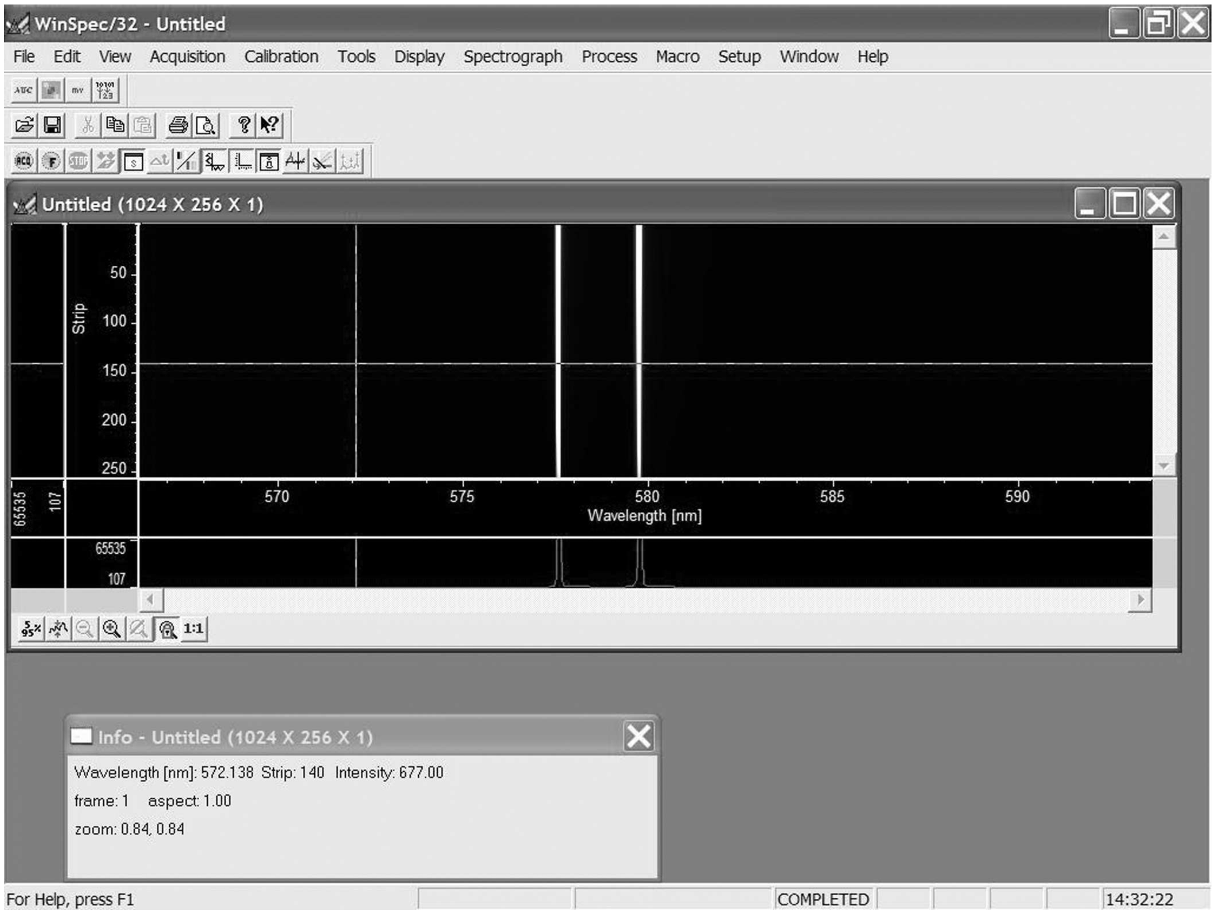

Fig. 5. *Main WinSPec/32 window.*

data on the displayed image are given. In our case the first line contains the coordinates of cursor position (wavelength in nm and the number of horizontal strip) and intensity in A/D units at that position. The second line reports the frame number and the aspect, and the third one the zoom data. The bottom of the window contains the status bar.

The CCD chip is thermoelectrically cooled by air cooled Peltier elements. The CCD temperature is controlled via the software. When the desired temperature is reached it will be stabilized to within 0.05°C of the selected value. The time required to achieve the stabilization is about 30 minutes.

The WinSpec software allows adding data from several pixels into a single pixel (binning) Rectangular groups of pixels may be binned. The binning is very useful in long-slit spectroscopy when one wants to keep the spectral resolution, not needing the spatial resolution. Then the 1xn binning can be used both to improve the S/N ratio and to reduce the readout time.

Readout speed is controlled by the software trough the controller. The conversion speed of the fast mode is 1 MHz. There are two more collection speeds: 100 kHz and 50 kHz.

Software allows the setting of exposure time from 0.001 seconds to hours. In practice, exposure times longer than half an hour usually have to be avoided because of the accumulation of signal from cosmic rays on the CCD image.

There are two modes of data collection: focus and acquire. In focus mode data are not stored but only shown on the monitor screen. This allows rapid refresh rate of the screen that is important in process of adjusting and setting the spectrograph. In acquire mode every collected image is stored except when the data acquisition is too fast.

WinSpec software controls trough a stepping motor the grating turret: changes the gratings and rotates the desired grating to an appropriate wavelength position. By defining the grating, detector and spectrograph parameters, software will adjust the grating to the adequate angle that will set the desired wavelength to the center of the screen. The abscissa scale is expressed in wavelength units. This grating-position wavelength calibration (or spectrograph calibration) is based on the grating equation from which the software calculates the grating angle of the selected wavelength value and operates the stepping motor to turn the grating to the appropriate position. For this calibration it is necessary to have at least one spectral line displayed on the screen (or zero order image of the slit). Once the grating is positioned at the chosen wavelength, the wavelength calibration should be performed for that grating position. Once the calibration spectrum is displayed on the screen the software finds the positions of the spectral lines (in pixels). By entering the corresponding wavelength for the lines the software will complete the wavelength calibration of the displayed spectral range by a least squares fit of the peak positions to a line or a polynomial.

3. RECIPROCAL LINEAR DISPERSION AND RESOLUTION

Reciprocal linear dispersion of SpectraPro spectrograph was measured at five, about 6 nm wide, spectral ranges around 350 nm, 400 nm, 430 nm, 550 nm and 580 nm, using a 10 μm wide entrance slit and the 1200 l/mm grating. The spectrograph entrance slit was illuminated by solar scattered light. The reciprocal linear dispersion was obtained by calibration of the observed solar spectrum using the solar spectral line atlas of Moore et al. (1966). Line identification was carried out by comparing the observed spectrum with that of the solar spectral atlas (Delbouille et al. 1973). During this procedure some difficulties in spectral line identification arouse, due to the very different resolutions of the observed and compared spectra. These problems were, for some spectral regions, overcome by smoothing the high-resolution solar spectrum until its resolution became comparable with that of the observed one. For illustration see spectra in Fig. 6. The measured reciprocal linear dispersion values in every spectral range were averaged and this average value was associated with the corresponding central wavelength of the spectral window. The variation of the reciprocal linear dispersion (nm/px) with wavelength is shown in Fig. 7. Taking into account the pixel size (26 μm) we obtain 1.02 nm/mm at 500 nm, in good agreement with the value 1.1 nm/mm given in specification of Acton Research Corporation.

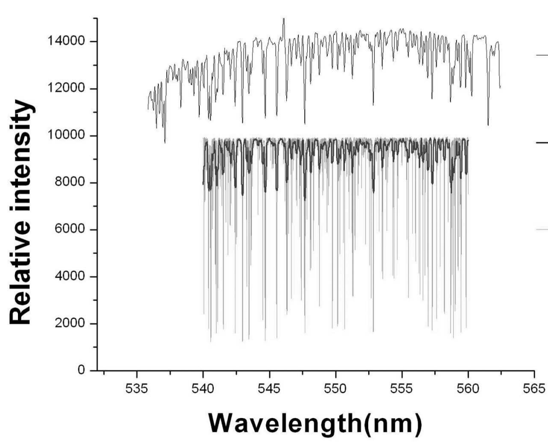

Fig. 6. *Observed solar spectrum (a), smoothed solar spectrum atlas (b) and high-resolution solar spectrum atlas (c).*

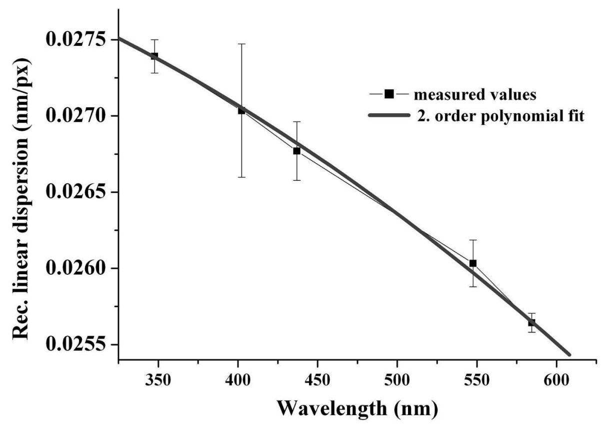

Fig. 7. *Reciprocal linear dispersion curve of spectrograph in the first order with grating 1200 l/mm.*

The spectral resolution (R) is defined by the relation:

$$R = \frac{\lambda}{\delta\lambda}, \qquad (1)$$

where λ is the wavelength and $\delta\lambda$ is the spectral purity, i.e. the wavelength spacing between two just separable lines at wavelength λ. Expressing the spectral purity trough grating parameters, the theoretical or diffraction limited spectral resolution of a grating can be given by simple formula:

$$R_{th} = mN, \qquad (2)$$

where m is the order of the spectrum and N is the total number of grating grooves (lines). For our grating with 1200 l/mm the first order resolution is 68 mm x1200 l/mm=81600. In practice, however, the spectrograph resolution is lower because the spectral line profiles are subject to broadening caused by the spectrograph optical elements. In practice the resolving power is less than the theoretical one due to the finite slit width, resolution of the CCD array, not ideal optical system (e.g. aberrations) and not adequate mode of entrance slit illumination, etc. The shape of the broadened line profile is characterized by the instrumental profile (I). The relationship between recorded spectrum (G) and the real spectrum (F) of the incident light can be expressed by

$$G(\lambda) = \int_{-\infty}^{+\infty} I(\lambda - \lambda')F(\lambda')d\lambda'. \qquad (3)$$

The instrumental profile is usually normalized so that

$$\int_{-\infty}^{+\infty} I(\lambda)d\lambda = 1. \qquad (4)$$

For determination of the instrumental profile we used our Hg(Ar) spectral lamp. As a first approximation we assumed that spectral lines produced by this spectral lamp have negligible widths in comparison to the width of instrumental profile. Thus the spectral line profile produced by Hg(Ar) lamp represents the instrumental profile. Under the present approximation we assumed further that the measured full width at half maximum (FWHM) of the instrumental profile is equal to the practical spectral purity ($\Delta\lambda$). Since the spectrograph will be linked to a telescope using optical fibers, the instrumental profile of the spectrograph for the 1200 l/mm grating is determined using our single-leg fiber optic bundle with fibers arranged as a slit pattern. This instrumental profile, measured with the fiber optic bundle alone, was compared to the instrumental profiles obtained when the same fiber optic bundle illuminated the entrance slit having the width (W) reduced to 5 μm and 10 μm. Fig. 8 shows the obtained (instrumental) profiles for the 576.9 nm spectral line. We chose these two values for the slit width, as they are typical for the 1200 l/mm grating. The slit width was measured in units of the basic slit width (d_o), which depends on the aperture ratio (a) of the spectrograph and wavelength:

$$d_o = a\lambda. \quad (5)$$

The aperture ratio is the quotient of focal length and the effective grating width ($w_{eff} = w_o \cdot \cos\beta$, w_o is the geometrical width of grating and β is the grating angle). Introducing in Eq. (5) the appropriate values of our grating, the basic slit width at 580 nm is about 5 μm. When the entrance slit is set to this width, the resolution is 83% of the theoretical value, but the brightness is only 42%. When the slit width is doubled (optimal width), the resolution decreases to about the half value, but the brightness rises to 86%. For our spectrograph the resolution at basic slit width should be about 68000. Our measurements gave only about 9300. The discrepancy between these values is mainly due to sampling pattern of the detector (CCD chip). Namely, it is required that each independent point at detector is sampled by a slightly more than two sampling elements (pixels). In our case this corresponds to about 0.05 nm, which leads to a resolution of about 10000. This value is in good agreement with the measured one. On the other hand, when the spectrograph is illuminated by the pseudo-slit of fibers, the size of the fiber image (200 μm) will define the resolution. The fiber image is sampled with about 7 pixels that give 0.18 nm for the spectral purity. Then the resolution is 3200, which is in good agreement with the measured value (~3300). That means that the Doppler-velocity measurement accuracy of our spectrograph is about 100 km/s. From this discussion we can conclude that for improvement of velocity measurement accuracy it is necessary to increase the dispersion. It can be done by increasing the grating constant or to use higher-order spectrum.

The instrumental profiles are normalized to unit area according to Eq. (4). In Table 1 the measured FWHM (i.e. the practical spectral purity) of instrumental profiles and the resolution (R) for 576.9 nm and 579.0 nm lines and their average values (Σ) are given. As it is expected, the narrowest instrumental profile is obtained for the smallest entrance slit width. Its FWHM is about 0.06 nm.

Table 1. Instrumental width (FWHM), resolution (R) for different entrance slit widths (W), and their average values (Σ) are given.

W (μm)	5	10	200
λ_1 = 577nm			
FWHM (nm)	0.061	0.106	0.173
R	9460	5440	3340
λ_2 = 579nm			
FWHM (nm)	0.063	0.109	0.174
R	9190	5310	3330
Σ(FWHM)	0.062	0.108	0.174
Σ(R)	9320	5380	3335

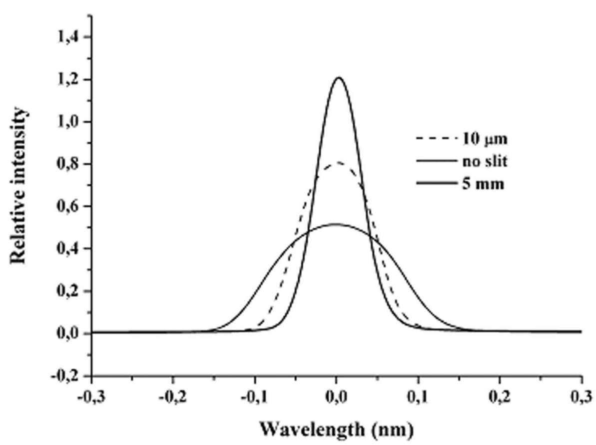

Fig. 8. *Instrumental profile for slit widths of 5 μm, 10 μm and for the fiber bundle pseudo slit (no slit).*

4. A POSSIBLE LINK BETWEEN TELESCOPE AND SPECTROGRAPH

As it was mentioned earlier in this paper it is necessary to have a flexible optical link between a telescope and our spectrograph. Since the spectrograph is rather large and cannot be attached directly to the telescope, the only solution is to realize a link by the use of optical fiber. Here we propose one possible solution for this link. The proposed set-up is very simple, but practical (Fig. 9).

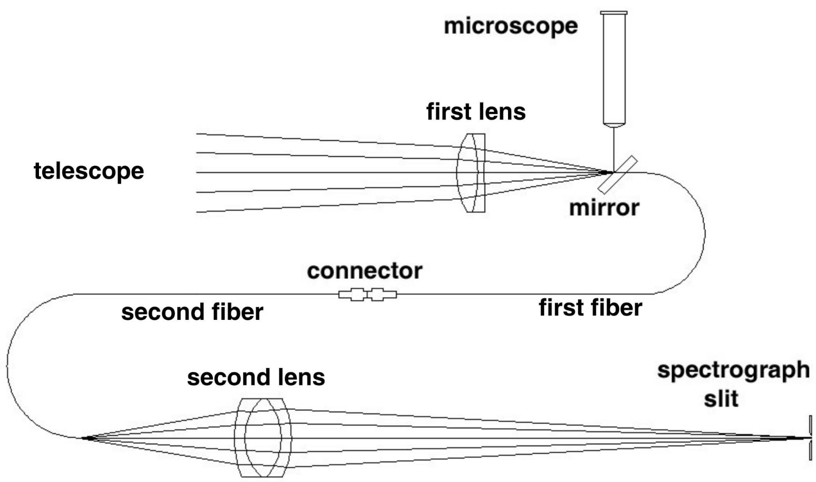

Fig. 9. *Optical link between telescope and spectrograph.*

The first lens (doublet) demagnifies the image of the star so that it will be contained within the diameter of the fiber core, without exceeding the numerical aperture of the fiber. An optimized doublet would be adequate. A 100 μm diameter fiber (first fiber) will collect all the light from the star. The mirror (preferably of metal) contains a small hole at 45 degrees. The mirror is mounted on a XY-translator to allow its precise movement in a plane parallel with the telescope image plane. The 100 μm fiber is glued into the hole so that its tip is in the mirror plane. The microscope enables viewing of the star image simultaneously with the fiber tip appearing as a "black hole" in the microscope. Focusing of the star image on the plane of the fiber tip can be made by adjusting the sharpest view of the "black hole" to coincide with the star image. When this is done the XY-translator allows adjustment of the star image upon the fiber tip. The coupling of the light into the fiber will be seen in the microscope as the "black hole" swallowing the star image. The advantage of this arrangement is that the coupling of light into the fiber can be viewed and adjusted during the exposure.

The fiber going to the spectrograph consists in fact of two identical fibers (first fiber and second fiber) joined together by an SMA - SMA connector (shown in the middle of the figure). The reason for this is that it is very practical to be able to disconnect the fiber coming from the mirror to observe the light coming out of it, thus being able to fine adjust the coupling into the fiber core by adjusting the XY-translator so that the light coming out of the fiber is as intense as possible. Alternatively, the output of the fiber from the mirror can be monitored by a fiber optic detector[1]. As disconnecting the fibers, viewing the output and fine adjusting, takes only a few minutes, it can be done during long exposures as well. Having the fiber split in this way allows disconnection without having to apply force to the spectrograph or the telescope, thus risking their alignments.

The fiber (second fiber) going further to the spectrograph cannot be the standard fiber-bundle from the spectrograph manufacturer, because of the losses induced by the mismatch of the numerical aperture of the fiber and the numerical aperture of the spectrograph. Therefore, a numerical aperture-matching lens (second lens) must be used. An optimized triplet will be adequate. The lens must image the fiber tip directly on the entrance slit of the spectrograph (see Fig. 9).

5. CONCLUSION

The practical spectral resolutions (spectral purity) of the SpectraPro spectrograph (1200 l/mm grating) when it was illuminated by a fiber optic bundle with fibers arranged in a 200 μm width pseudo-slit pattern and when the same fiber optic bundle illuminates the spectrograph entrance slit of basic width (5 μm) and of optimal width (10 μm) are determined from the appropriate measured instrumental profiles. The spectral resolutions for 5 μm, 10 μm and fiber optic bundle are about 9300, 5400 and 3300 respectively. For our spectrograph the calculated resolution at basic and optimal slit width should be about 68000 and 38000. The degradation of resolving power by a factor of about 7 between calculated and measured values is mainly due to sampling pattern of the detector (CCD chip). On the other hand, when the spectrograph is illuminated by the pseudo-slit of fiber, the calculated (about 3200) and the measured resolution for the fiber optic bundle are in good agreement, since the size of the width of pseudo-slit image (200 μm) at CCD chip defines the resolution. That means that the Doppler-velocity measurement accuracy of our spectrograph is about 100 km/s when the pseudo-slit of fiber is used. Therefore, we can conclude that our spectrograph is suitable for

[1](see for instance sensor at `http:// www.wpiinc.com/WPI_Web/Spectroscopy/VIS_%20UV_detectors.html`)

recording low-resolution spectra of stars and asteroids, medium-resolution spectra of relatively bright stars and studies of the variations in highly broadened spectral line profiles. For determination of gas movements in circumstellar disks as well as for radial velocity measurements of close binary stars, where velocities of several hundred km/s often are observed the resolution should be increased. Decreasing of the fiber optic bundle pseudo-slit width, increasing the grating constant, or use of the grating in higher-order spectrum can do it.

For optical link between a telescope and our spectrograph a very simple but practical set-up is proposed. The advantage of this set-up is that it enables viewing of the stellar image simultaneously with the fiber tip and the coupling of light into the fiber can be viewed and adjusted during the exposure. The link between telescope and spectrograph is realized by two identical fibers joined together by an SMA - SMA connector. By disconnecting the fiber feeding the spectrograph from that coming from the telescope focal plane it can observe the light coming out of it, thus being able to fine adjust the coupling into the fiber core.

The spectrograph's reciprocal linear dispersion of 1.02 nm/mm at 500 nm is determined from the empirical dispersion curve obtained from observed solar spectra in the spectral range 350 - 600 nm. Since this value is in good agreement with the value (1.1 nm/mm) given in specification of Acton Research Corporation, we can conclude that the optics of our spectrograph is satisfactory.

Acknowledgements – This work was supported by the Ministry of Science and Environmental Protection of the Republic of Serbia (Contract No. 1191 and 1951). The authors are grateful to Dr. Peter Lindblom, Systematix AB, Sweden, for valuable discussions and for comments.

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КАРАКТЕРИСТИКЕ ЗВЕЗДАНОГ СПЕКТРОГРАФА АСТРОНОМСКЕ ОПСЕРВАТОРИЈЕ У БЕОГРАДУ

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У овом раду приказане су главне карактеристике новог спектрографа SpectraPro-750 Астрономске опсерваторије у Београду. Одређен је инструментални профил спектрографа при примени оптичке решетке 1200 l/mm и оптичког кабла са излазом у облику псеудо прореза. Овај инструментални профил је упоређен са профилом који се добија када је улазни прорез различитих ширина и осветљен посредством поменутог оптичког кабла. Из одговарајућих инструменталних профила одређена је практична спектрална чистоћа и моћ спектралног разлагања за различите ширине улазног прореза. Одређена је и промена реципрочне линеарне дисперзије са таласном дужином у спектралној области од 350 nm до 600 nm. Поред тога, дат је и предлог за решење оптичког повезивања спектрографа са телескопом.