The 182 cm Telescope B&C Spectrograph: Three useful experimental relationships

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Abstract

The relation between the focus position and the temperature for the B&C spectrograph is derived together with the experimental resolution limit of the spectrograph itself.
The spatial scale of the spectrograph on the detector is measured from binary stars observations. The objects were selected in a general sample extracted from the Hipparcos Input Catalogue in order to plane similar observations for A–FOSC instrument.

1 Introduction

In the last three years the operational and observative conditions with the B&C spectrograph have been improved by a set of both mechanical (Chiomento and Traverso 1994) and technological (Fantinel and Claudi 1995) improvements which have permitted to address and solve some instrumental problems. Moreover it has been possible to investigate in detail the real performance of the instrument.
In particular, in a previous technical report (Claudi et al. 1995a) the characteritics of the collimator focus of the spectrograph together with some mechanical troubles affecting the measurements carried out with this instrument were pointed out.
In this technical report we present an analysis of the structural and performance characteristics of the spectrograph. In particular we discuss the spectrograph focus shift caused by temperature variation, the limit of the resolution and the spectrograph scale on the detector.

Similar observations have been planed in order to determine the scale on the detector for A–FOSC.

A sample of objects as target for such a measurement has been selected.

2 The Temperature – Focus Relation

The theoretical relation between the focus shift and the temperature variation is given by (Bowen 1962):

$$\delta y = f_K(1 + \frac{f_K}{f_C}) \cdot (\rho_f - \rho_m) \cdot \Delta t \qquad (1)$$

where f_K and f_C are the focal length of the camera and of the collimator respectively, while $\rho_f - \rho_m$ is the difference between the two expansion coefficients of the material of both the spectrograph frame and the collimator mirror.

The grating volume variation with the temperature, if any, cannot account for the focal length variation, since the collimator makes parallel the rays before the plane surface of the grating disperses them.
On the contrary the spacing of the lines of a grating shifts with the temperature, but the effect (movement of spectral lines if temperature changes during exposure) becomes important only for high resolution spectrographs due to the small value of the displacement of spectrum per ^{o}C coefficient (≈ 0.010Å/^{o}C for pyrex gratings (Bausch and Lomb 1976)).

In order to evaluate experimentally the relation (1) we have collected an historical log (since June 1993) of the focus and dome tem-

Figure 1: Least square linear fit of experimental data for the temperature – focus position of the spectrograph collimator. The data are relative to the three indicated gratings available at “ Copernico” telescope

perature.

For the three most exploited gratings (150, 300, 600 gr/mm) the data were analyzed with the least square fitting on a function $y = mx + q$ (see Figure 1).

The results obtained are listed in Table 1 where in the first column the grating is indicated, the second column shows the correlation coefficients. From the third column to the sixth we have the coefficients of the linear fit with their own statistical errors. The last two columns contain the broadcast error for a future measurement.

As it is easy to see from the results, the angular coefficient for the three relations is the same within the error. This is not true for the coefficient q.

This situation reflects the fact that different gratings have different focus positions (Claudi et al. 1995a) and it is probably due to

Figure 2: The change of σ_{fit} with different values of the two parameters α and β

geometrical differences in gratings construction.

To improve the determination of the t – F.P. relation we have reported the focus position measured for the 300 and 600 gr/mm gratings to that for the 150 gr/mm one making use of two additional parameters: α for the 300 gr/mm grating and β for the other one. Successively, modifying the two parameters, a least square fit for all data was guessed until a minimum value for σ_{Fit} was found. In Figure 2 the change of σ_{Fit} with the α and β parameters is shown.
The minimum was obtained for the following values:

gr/mm	ρ	m	σ_m	q	σ_q	σ	P.E.
150	-0.97	-0.110	0.009	12.9	0.1	0.1207	0.08
300	-0.93	-0.114	0.020	13.1	0.2	0.1190	0.08
600	-0.96	-0.110	0.010	13.7	0.2	0.1963	0.10

Table 1: Least square fitting results. The Probable Error is $(2/3)\sigma$

$$\begin{array}{lcrlcr}
\alpha & = & -0.175 & \beta & = & -0.8 \\
\mathrm{m} & = & -0.109 & \mathrm{q} & = & 12.92 \\
\sigma_{Fit} & = & 0.147 & \mathrm{P.E.} & = & 0.09
\end{array}$$

The next step was to make the least square fit again on data of each grating to determine the q coefficient (the focus position at T=0^{o}C) in order to evaluate an appropriate change law.

Figure 3: **A**: The relation between the dispersion and the focus position at 0^{o}C. **B**: The same of **A** but in the indicated abscissa. The linear fit is also shown

The results are illustrated on Figure 3a for each linear dispersion value, while the linear fit is shown in Figure 3b. The change law for the focus position at 0^{o}C is:

$$F.P.(0^{o}C) = \frac{5.97}{\log D} + 10.52 \tag{2}$$

The F.P.(0^{o}C) evaluated for each grating are shown in Table 2.

For example, the t – F.P. relation for the 1200gr/mm grating is:

$$y = -0.11 \cdot t + 14.20 \tag{3}$$

where y is the value indicated by the collimator vernier and t is the dome temperature in ^{o}C. The focus position evaluated utilizing equation (2) has a determination error of ±0.09 *div*. This error corresponds

Grating gr/mm	Dispersion D Å/mm	F.P.(0^oC) div.
1200	42	14.20
600	85	13.61
400	127	13.20
300	169	13.20
150	339	12.86

Table 2: The F.P.(0^oC) evaluated for each grating. The values of dispersion are given in Claudi and Cremonese 1993

to a minimum dome temperature variation ($\Delta t \approx 1^oC$) that it is not possible to take into account refocusing the spectrograph.

As a *Fall-out* we obtain the subsequent result: a comparison between equations (1) and (3) permits us to derive:

$$(\rho_f - \rho_m) = 0.0002 \quad (^oC)^{-1}$$

where the conversion factor between *div* and *mm* for the collimator vernier was utilized (Claudi et al. 1995a)

3 The Resolution Limit

In the slit spectrograph a narrowing of the entrance slit is sufficient to increase the apparent resolution of the instrument. It is known that a limit exists in narrowing the entrance slit: the *critical slit width* (see for example Meltzer 1969) which is reached when the first diffraction minima are at the edge of the aperture. This implies that narrowing the slit below the *critical slit width* results in a loss of light with a consequent degradation of the spectrum. For astronomical spectrographs this limit is principally defined by the seeing:

$$W_{min} = \beta \cdot f_T$$

where β is the angular dimension of the seeing circle and f$_T$ the focal length of telescope. For the C.^{ma} Ekar 182 telescope (f$_T$=16380 *mm*) with a seeing value of 1 *arcsec*, we obtain a W_{min}=98 μm. This value is of a factor 10 greater than the W_{min} obtaining in the diffraction limit condition for a wavelength of 7500 Å.

To investigate the real resolution limit of the spectrograph we have collected spectra of the comparison lamp for each available grating,

Figure 4: The theoretical (heavy line) and the experimental chromatic resolution (the data points).

decreasing the slit width from 300 μm to the mechanical limit of the slit itself ($5\mu m$). The central wavelength for each grating was maintained at $\approx$ 7500 Å in order to have a comparable sample. The data were reduced with IRAF.

The results are shown in Figure 4 where for each grating the resulting FWHMs are plotted versus the corespondent slit width. The relative theoretical chromatic resolution:

$$R_c = 10^4 \cdot \frac{W}{Nmf_C} \cdot \cos(i + \Phi/2) \tag{4}$$

(the heavy continuous line) is also plotted (Heydari – Malayeri et al. 1989).

The slit width W is given in μm, the collimator focal distance f_C in mm, the numbers of grooving N in mm^{-1} while m is the spectral order (1 for our data), i and Φ are respectively the inclination and the grating configuration angle (49^o).
As it is easy to see from the figure, the experimental chromatic resolution is really different from the theoretical curve.

The degree to which the theoretical resolution is attained depends on the optical quality of the grating surface, the uniformity of groove spacing, and the quality of all the associated optics. Moreover, other experimental problems like air currents and vibrations can seriously affect the measurements.
All these occurrences however do not mean a loss of linearity, as it is possible to observe in the experimental data with FWHM $\leq$ 2 pixels. The departure from the linearity might be mainly caused by two factors.
The first one is that the effective CCD spectral resolution is the convolution of R_c with the detector pixel size. At dimension $\leq$ 2 pixels the spectral information can be distorted by the sampling of the detector. On the other hand, the algorithm utilized to evaluate the FWHM is practically a gaussian fit on the spectral line and it is possible that it reaches its limit for width $<$ 2 pixels.
It is possible to obtain the limit of the resolution for each grating performing a double linear fit for each sample in order to evaluate the position of the break.

The results, shown in Table 3, point out that it is impossible to obtain a resolution better than 1.7 pixels on average with a slit width that range from 1 to $\sim$ 2 arcsec.

Grating	W		FWHM	
gr/mm	arcsec	μm	Å	Pixel
1200	1.0±0.1	79±8	1.46±0.01	1.46±0.01
600	1.2±0.1	99±4	3.08±0.04	1.62±0.01
400	1.3±0.1	106±6	5.20±0.06	1.79±0.02
300	1.2±0.1	96 ±9	7.01±0.07	1.84±0.02
150	1.3±0.1	101±11	14.4±0.2	1.80±0.03

Table 3: The minimum slit width and the correspondent resolution limit measured for each grating available at the "Copernico" Telescope.

4 The Spectrograph Scale

The spectrograph scale on the detector is theoretically given by the relation:

$$S = \frac{206265}{F_{eff}} \quad arcsec \cdot mm^{-1} \tag{5}$$

where the effective focal length F_{eff} is given by:

$$F_{eff} = f_{\#K} \cdot D_T \tag{6}$$

with D_T the telescope aperture and $f_{\#K}$ the effective f–number of the camera which depends by the collimator aperture D_C and by the camera focal length f_K:

$$f_{\#K} = \frac{f_K}{D_C}$$

In the case of the Boller and Chivens spectrograph mounted at the "Copernico" telescope these quantities have the following values:

- $f_K = 188.32\ mm$
- $D_C = 90\ mm$
- $f_{\#K} = 2.1$
- $F_{eff} = 3822\ mm$

with these values from the equation (5) and for the chip exploited with the B&C (TH7882) it is possible to calculate the theoretical spectrograph scale on the detector:

$$S = \begin{cases} 53.97\ arcsec/mm \\ 1.24\ arcsec/px \end{cases}$$

Figure 5: The finding chart and some characteristics of HIC 12886 as extracted from the Hipparcos Input Catalogue

To obtain a measurement of the spectrograph scale we select a sample of double stars or multiple systems with known separation and positional angles (PA) from the Hipparcos catalogue. If ρ is the angular separation of two stars and δ is the same separation on the chip and Θ the PA measured from the N–S direction towards West, the spectrograph scale is given by:

$$S_{BC} = \frac{\rho}{\delta} \cdot \sin\Theta.$$

We can put a threshold value for the stars angular separation (ρ) in order to measure the spectrograph scale with a relative error less then 10%. The greater contribution to the relative error for S_{BC} is given by the δ measurement. since the value of ρ and Θ are tabulated in the catalogue without measurement errors. Moreover it is possible do not consider the PA term (see ahead). If we consider as maximum measurement error for δ the pixel dimension ($23\mu m$ for the Thompson TH7882 Thick UV–coated CCD utilized for the B&C spectrograph) we obtain a minimum δ value of $230\mu m$ equivalent to a separation in the sky of:

$$\rho_{min} = 12.41 arcsec$$

greater than the resolution power of the 182 cm Telescope (0.1 $arcsec$).

Figure 6: Transversal section of the CCD at the B&C spectrograph frame for the binary system **HIC 12886**

The object utilized for the measurement was the double star system selected from the printed version of the Hipparcos Input Catalogue

(Turon et al. 1992) with the Hipparcos catalogue number **HIC 12886**. The principal characteristics together with the PA and the separation of the B components and the finding chart are shown in Figure 5.
The observations were carried out with the Boller and Chivens spectrograph equipped with the 300 gr/mm^{-1} grating. A transversal section of the frame obtained is shown in Figure 6.
The PA of the **HIC 12886** system is 269^o. This fact introduces a new term in the measurement errors balance discussed before, but it is easy to see that:

- The contribution of the position angle term becomes less than 0.05 for PA values between the extremes $(\frac{\pi}{2} \pm \frac{5}{100} \cdot \pi) \pm k\pi$ fulfilling the required threshold for the relative error stated before for the scale measurement. The value of Θ employed is included in the interval defined before.
- the optimal PA of the binary or multiple component in order to evaluate the spectrograph scale is $\frac{\pi}{2} \pm k\pi$ where $k = 0, 1$. In this case in fact the PA relative error term discussed before becomes negligible.

Using different transversal frame sections we have evaluated the distance between the positions of two maxima of the stars. A gaussian profile fitting was performed.

First, a linear fit of the corespondent maxima positions on the frame was evaluated and after a coordinate transformation was performed in order to correct the data for the possible misalignment of the frame from the dispersion direction. This latter gives the values of the separation between two parallel straight lines.

The mean separation obtained corresponds to the subsequent spectrograph scale:

$$S_{BC} = \begin{cases} (51.88 \pm 0.09) \ arcsec/mm \\ (1.193 \pm 0.002) \ arcsec/px \end{cases}$$

This value is slightly different from the theoretical one. The discrepancy can be due to the fact that we have not considered that a diffuse method to correct the chromatic aberration (in first approximation) of the spectrograph camera is to incline its focal plane (see the spot diagram of the Galileo Camera in Falomo and Pertile, 1986). In this case the actual detector scale results reduced by a factor $\cos\theta$.

4.1 A–FOSC scale measurement plane

In order to plane similar measurements for both future checks of the spectrograph scale and the A-FOSC scale on chip, the minimum projected separation in the sky for two different CCD Chips has been

Collimator Focal Length*	252.1	*mm*
Beam Diameter	28.0	*mm*
Camera Focal Length*	146.3	*mm*
Pixel size Chip Loral	15	μm
Pixel Size Chip Tektronix	27	μm

Table 4: The A–FOSC optical characteristics and the CCD chips pixel size utilized to evaluate the separation limit measurable with a relative error of 10%. The values indicated with * are taken by Merighi et al. 1994

evaluated for the characteristic lengths of the A–FOSC optics as applied to the "Copernico" Telescope (see Table 4).

The limits are:

$$\rho_{min} = \begin{cases} 5.9 \text{ arcsec} & Chip \;\; Tektronix \\ 3.2 \text{ arcsec} & Chip \;\; Loral \end{cases}$$

We have selected a sample of objects observable with the 182 cm telescope with a separation $\rho > \rho_{min}$ and a PA $\Theta = 90^o$ or $\Theta = 270^o$ from the Hipparcos Input Catalogue. The sample selected is shown in Table 5. For a more detailed description of the quantities involved we defer to the documentation of the Catalogue as reported by Battistini et al. 1994.

All the objects in the table are usable for A–FOSC equipped with the Loral Chip, while only the objects marked with † and $\star$ are utilizable for A–FOSC with the Tektronix chip. Finally for the B&C spectrograph the objects indicated by $\star$ can be used.

5 Conclusions

In this technical report we have obtained three relations on the structural and perfomance characteristics of the B&C spectrograph. These relations are useful both for setupping and observing operations.

In particular we have derived a relative and absolute experimental law of the shift spectrograph focus shift with the temperature variations. The temperature measurement errors do not allow to correct the focus shift caused for temperature variations less than 1 ^oC. This situation can be improved with the new meteorologic station implemented at Ekar (Claudi et al. 1995b). This station reads information coming from measurement probes placed on the telescope mirror, closer to the instruments, with a measurement error of 0.01 ^oC..

HIC		$\alpha_{(2000)}$			$\delta_{(2000)}$		m_V	Θ	ρ	δ_{mag}	Notes		
Number	HH	MM	ss	DD	PP	ss		(*Deg.*)	(*arcsec*)				
16410	03	31	19.790	27	34	17.800	6.992	270.00	13.400	0.50	AB	S	⋆ †
21963	04	43	16.218	−09	37	05.280	8.000	90.00	8.500	5.20	AB	S	†
23053	04	57	40.240	−05	44	54.800	10.300	90.00	28.500	0.50	AB		⋆ †
33167	06	54	13.860	06	41	16.900	7.400	90.00	115.900	0.10	AB	S	⋆ †
42412	08	38	56.315	−06	50	54.190	7.100	90.00	7.600	6.60	AB	S	†
56598	11	36	14.626	03	18	03.810	7.100	90.00	3.600	5.70	AB	S	
99261	20	08	58.090	28	41	03.500	9.400	90.00	12.000	4.00	AB		†
101420	20	33	11.110	64	41	30.300	8.644	90.00	6.900	2.20	AB		†
106637	21	35	57.400	26	22	10.900	9.270	90.00	12.900	0.20	AB		⋆ †
113414	22	58	08.980	30	21	55.200	9.600	270.00	58.900	0.70	AD		⋆ †
113621	23	00	42.530	31	04	59.200	6.600	90.00	3.400	2.50	AB	S	
116081	23	31	19.558	42	04	08.010	8.900	90.00	7.700	4.10	AB		†

Table 5: The object sample selected by the Hipparcos Input Catalogue. See text

The minimum resolution of the spectrograph can be reach with a minimum slit width ranging between $1 \div 2$ *arcsec* depending on the grating employed. This result is comparable with the theoretical result obtained for a good seeing ipothesys (1 *arcsec*). Since the average seeing for C^{ma} Ekar in 1994 was evaluated in $2 \div 2.5$ *arcsec* it is quite impossible to reach the limit of the instrument.

Finally we have evaluated the spatial scale of the spectrograph on the chip TH7882 Thick UV - Coated exploiting objects selected from the Hipparcos Input Catalogue.

A set of suitable objects was individuated in order to perform future analogous measurements with the A–FOSC instrument.

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