FROM CZERNY-TURNER TO A MULTICHANNEL SPECTROGRAPH, FROM PHOTOGRAFIC TO CCD DETECTORS

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ABSTRACT

In 1980s two medium-size horizontal solar telescopes 50/35000 cm with large spectrographs Czerny-Turner made by Carl Zeiss Jena were installed in the Ondřejov observatory. After two decades of utilization the electronics and all the control system of both instruments were replaced by an up-to-date technique. According to the recent scientific plans, one of the Czerny-Turner spectrographs will be used as a multichannel one. Then, instead of a large scale photographic detector, up to 5 CCD cameras will be used. The aim of this contribution is to optimize the distribution of the cameras in the limited space for obtaining the best angular spectra resolution in particular selected spectral lines and to calculate the optimized focal lengths of the cameras for having a right size of the image projected on the CCD-chip.

1. INTRODUCTION

The Czerny-Turner-spectrographs in the Ondřejov observatory called HSFA1 and HSFA2 according to the German name *Horizontal-Sonnen-Forschungs-Anlage* („horizontal device for solar research") have been explored for much than two decades. They are now in a process of modernization. In this article we will describe the reconstruction of the optical parts of the spectrograph of the HSFA2, which is supposed to be used as a multichannel spectrograph operating simultaneously in several diagnostically important spectral lines. There is already an older multichannel spectrograph in Ondřejov observatory, the MFS, *Multichannel-Flare-Spectrograph,* which has been used for five decades. The reasons for reconstruction of the one-way-spectrograph HSFA2 are as follows.

1.1 Multichannel Flare Spectrograph

The MFS has a small angular and chromatic resolution (angular resolution 0.72" for Hα, the chromatic resolution is 54.70 mÅ for Hα in the second order). The spectrograph room is placed in the main building of the solar physics department, on a rather busy site. Anyhow, the spectrograph room has a double-floor, the utilization of the building causes shakes which influence the optical beam. The height of the coelostat above the ground is about four meters. One of the advantages of the MFS is the possiblity to activate and operate it in a simple way. Further, the MFS could be simply modified and it is also simple to add other cameras to work simultaneously.

1.2 HSFA2

The high quality equipment of the HSFA2 was made by *Carl Zeiss, Jena.* There is a better resolution (angular resolution is 0.33" for Hα, the chromatic resolution is 12.60 mÅ for Hα in the fourth order) and high quality optics. The HSFA2 is placed about 400m far away from the main building in a forrest. There are no streets and buildings in the neighbourhood of the spectrograph room or other unwanted source of air-convection. The height of the coelestat above the ground is about 6 m. But there are several disadvantages. The HSFA2 is more complicated to activate due to the installed hydraulic system which is usable only by temperature above 5°C. Other problem is that the grating and objective were dedicated for configurations of larger detectors. But the main problem is the fact that we have a limited space inside the spectrograph-room. The long and narrow room was designed for a one-way-spectrograph.

In future we have to take a special attention to the mechanical problems of the spectrograph. We have to solve problems of oscillations: we think about putting the camera mirrors on special pneumatic tables or some other constructions which are able to minimize oscillations.

2. PRINCIPLES OF CALCULATION

On one hand we have fixed parameter of the configuration of the telescope (feeding of the spectrograph), the diffraction grating and the cameras. We already decided which CCD-cameras will be used,

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so the parameters of the cameras (size and amount of pixels and spectral sensitivity) became also fixed. The already available grating should be used due to minimizing the costs. On the other hand we have variable parameters which had to be combined and optimized.

2.1 Fixed Parameters

- diameter of the telescope primary mirror D_T=500 mm
- focal lentgh of the telescope primary mirror f_{mirr}=35 m
- focal lentgh of the collimator mirror f_{coll}=10 m
- Diffraction grating
  - Bausch & Lomb, plane, replica
  - the blaze angle of the diffraction grating ϕ=51°
  - the width of the diffraction grating W=206 mm
  - the height of the diffraction grating H=154 mm
  - number of grooves per mm C=632.1 mm^{-1}
- Camera
  - VDS Vosskuehler: CCD-1300LN
  - size of one pixel s_P=6.7µm x 6.7µm
  - size of the chip $s=p_H$ x p_V=1280(H) x 1024(V) pixels

2.2 Variable Parameters

- angle of incidence ε (changeable by rotating the grating)
- diffraction angle α
- wavelength of light λ (choosen spectral lines)
- spectral order n
- focal length of camera mirror f_{cam}

2.3 Choosen Spectral Lines

From astrophysical purposes we choose following list of spectral lines. The sensitivity of the chip η [in %] is given in the third column:

• Ca IR	(8542 Å)	7.2
• Hα	(6563 Å)	28.5
• D3	(5875 Å)	45.0
• Hβ	(4861 Å)	49.8
• CaK	(3934 Å)	22.4

3. CALCULATION

3.1 Sagittal Direction

The sagittal (vertical) direction represents the conditions of the telescope of the spectrograph. There are two main conditions which had to be fulfilled. First, the angular resolution of the telescope δ should be projected not less than on one pixel due to the Rayleigh criterion. The second condition means that the angular resolution δ should be smaller than the scale S in the focal plane.

$$\delta['']=2.52\times10^5\frac{\lambda}{D_T} \tag{1}$$

The angular resolution of the telescope δ depends on the wavelength and on one parameter of the telescope.

$$S=\frac{206265}{F_{eff}} \tag{2}$$

The scale S in the focal plane depends on the effective focal length F_{eff}. F_{eff} can be calculated in following way:

$$F_{eff}=\frac{f_{cam}}{f_{coll}f_{mirr}} \tag{3}$$

Having this, the scale S in the focal plane can be written in such a way:

$$S=206265\frac{f_{coll}f_{mirr}}{f_{cam}} \tag{4}$$

Finally, we can calculate the lower limit of the focal length of the camera mirror f_{cam}:

$$f_{cam}=\frac{206265 f_{coll}}{f_{mirr}S} \tag{5}$$

Schema of calculation in the sagittal direction is as follows:

1. Calculate the angular resolution of the telescope δ.
2. Respecting a condition concerning the scale S in the focal plane, choose a value for the scale S.
3. As the scale S depends on the focal length of the camera mirror f_{cam}, calculate the lower limit of the focal length of the camera mirror f_{cam} in sagittal direction.

3.2 Meridional Direction

The meridional (horizontal) direction represents the conditions of the spectrograph only. There was one condition which we accepted. It should apply: An interval of wavelength equivalent to the chromatic resolution $\Delta\lambda$ [mÅ] has to be projected on two pixels of the chip. The value of one pixel is choosen due to the Rayleigh criterion and we choose the value two instead of one for having a reserve.

The chromatic resolution $\Delta\lambda$ depends beside the spectral order n only on the wavelength λ and the grating.

$$\Delta\lambda = \frac{\lambda}{WCn} \tag{6}$$

The projection of the interval of wavelength equivalent to the chromatic resolution $\Delta\lambda$ is the linear dispersion $d\lambda/dx$. Generally, the linear dispersion $d\lambda/dx$ can be calculated in following way:

$$\frac{d\lambda}{dx} = \frac{\cos\alpha}{f_{cam}Cn} \tag{7}$$

The linear dispersion $d\lambda/dx$ depends on the focal length of the camera mirror f_{cam}. We can calculate the focal length of the camera mirror f_{cam}:

$$f_{cam} = \frac{\cos\alpha}{\frac{d\lambda}{dx}Cn} \tag{8}$$

Schema of calculation on the meridional direction is as follows:

1. Calculate the chromatic resolution $\Delta\lambda$.
2. Respecting a condition concerning the projection and so of the linear dispersion $d\lambda/dx$, choose a value for linear dispersion $d\lambda/dx$.
3. As the linear dispersion $d\lambda/dx$ depends on the focal length of the camera mirror f_{cam}, calculate the lower limit of the focal length of the camera mirror f_{cam} in meridional direction.

3.3 Diffraction Angle α

The diffraction angle α follows from the grating equation:

$$\sin\varepsilon + \sin\alpha = \lambda Cn \tag{9}$$

The angle of incidence ε is measured between the beam (from collimator to the grating) and the grating normal. The diffraction angle α is the angle between the grating normal and the diffracted light.

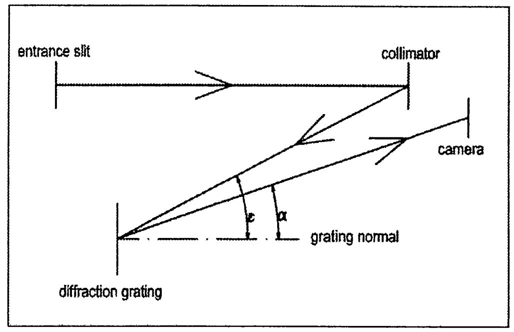

Fig. 1. Representation of the grating equation

3.4 Intensity of Light

The intensity of light I is calculated in a following way:

$$I = \left(\frac{\sin\left(n\pi C\left(\cos\phi - \left[\tan\frac{1}{2}(\varepsilon+\alpha)\right]\right)\right)}{(n\pi C)\left(\cos\phi - \left[\tan\frac{1}{2}(\varepsilon+\alpha)\right]\right)} \right)^2 \tag{10}$$

In fact, the intensity I depends on the angle of incidence ε, the diffraction angle α, the spectral order n, the blaze angle of the grating ϕ and due to the grating equation also on the wavelength of light λ. In Fig.2 one can see an example of an IDL-code output. It shows how the intensity changes with the wavelength. The angle of incidence ε and the spectral order n are input parameters. One can see that the lobes of intensity are getting narrower for higher orders. Maximum intensity occurs when:

$$\alpha + \varepsilon = 2\phi \tag{11}$$

We will denote the diffraction angle α with maximum intensity α_{max}.

$$\alpha_{\max} = 2\phi - \varepsilon \tag{12}$$

Existing of narrow lobes of intensity in higher spectral order means: If one works in higher orders, a sufficient value of intensity I can be obtained only for a small deviation from α_{max}. The direction of the distribution of the usable spectral lines will be in a small interval. This is due to the fact that all the diffraction angles α had to be nearly in the same direction (because when the deviation will be too large the intensity will not be sufficient). In the first or in the second spectral order the main maximum of intensity I is more expanded. So we can have also a sufficient intensity when we do not hit α_{max} exactly. That means that the diffraction angles are widely dispersed. And then we have a much better distribution of light in space.

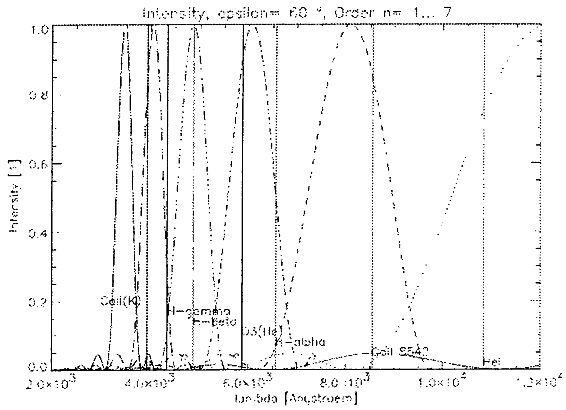

Fig. 2. The dependence of intensity on λ for given ε = 60° and n from 1 to 7.

3.5 Comments Concerning Calculation

There had to be pointed out that there are no problems in sagittal direction. The calculated focal lengths of the camera mirrors are in all cases feasible for our case. So the calculation for the meridional direction is more important. In the most cases there is not enough space in the spectrograph room for the calculated distribution of light and focal lengths of cameras. One had to have in mind the above mentioned fact that the room was made for a one-way-spectrograph. The other problem are obstacles: We want to put the cameras on the fundament beside the diffraction grating and they (as well as the objectives) had not to shadow the optical beam.
All the formulas are as in [1].

3.6 Calculation step by step

1. Find out possible α with the grating equation for combinations of λ, ε, n.
2. Check the intensity of light I.
3. Calculate f_{cam} for choosen λ, ε, α, n.
4. Check the possiblity for realization: if it is not realizable, start again with point 1.

4. PRACTICAL APPLICATION

4.1 Excel-Code

As mentioned earlier there were a lot of possibilities for combination of the variable parameters. To make the calculation more efficient we wrote a code in Excel. This code works in that way, that any parameter could be changed and all necessary values will be recalculated immediately. Following parameters could be entered and will influence the calculation:

- angle of incidence ε
- wavelength of light λ (choosen spectral lines)
- spectral order n (but the code suggest an optimized n)
- size of one pixel s_P
- size of the chip s
- number of grooves per mm C
- the width of the diffraction grating W
- the blaze angle of the diffraction grating ϕ
- diameter of primary mirror D_T
- focal length of primary mirror f_{mirr}
- diameter of collimator mirror D_C
- focal length of collimator mirror f_{coll}

We are also able to change the mentioned condition on how many pixels the chromatic resolution $\Delta\lambda$ and the angular resolution δ should be projected on.
Following values will be calculated or found:

- intensity of light I for every choosen line
- sensitivity of the chip η for every choosen line
- the optimized width of the entrance slit a_s for every choosen line
- diffraction angle α for every choosen line
- chromatic resolution $\Delta\lambda$ for every choosen line
- linear dispersion $d\lambda/dx$ for every choosen line
- focal length of camera mirror f_{cam} optimized in meridional direction for every choosen line
- angular resolution δ for every choosen line
- focal length of camera mirror f_{cam} optimized in sagittal direction for every choosen line
- scale S in the focal plane for every choosen line

There is also a possibility to change the optimized focal length of camera mirror f_{cam} and the code will calculate the new linear dispersion $d\lambda/dx$ and we can examine if the suggestion was sufficient or not.

4.2 Solution

We tried a lot of possibilities of angles of incidence ε which have enough intensity in the selected spectral lines. Our recommendation is the angle of incidence ε=60°. Then we have sufficient intensities and an acceptable distribution of light. But it had to point out that the grating luminosity will be reduced in the way $\cos\varepsilon=\cos 60°=0.5$. That means that we have higher luminosity for smaller angle of incidence ε.
The distribution of the spectral lines can be seen in Fig.3. The segments $a \ldots e$ present the several spectral lines. The length of the segments presents the calculated focal lengths of the camera mirror in the meridional direction.

The intensity and the spectral order in the selected lines are as follows:

segment	spectral line	intensity [%]	spectral order n
a	Ca IR	84.74	3
b	Hα	50.46	4
c	D3	90.64	4
d	Hβ	99.99	5
e	CaK	84.56	6

There are problems for using all five lines. Line *c* and *e* are too close to each other. It is not possible to have two cameras in such a small distance of angles. The calculated focal lengths of the lines *d* and even of line *e* are too long for the room. It would be a good possibility to have one table where all the objectives can be put on. But in this case the calculated focal lengths of the lines *a* and *b* are too short. The problems are caused by the following reasons:

1. the dimensions of the spectrograph room
2. the parameters of the diffraction grating

The grating has a blazing angle of ϕ=51°. We had to work in spectral orders from 3 to 6. As mentioned in 2.3: higher orders mean always not so well distributed light. The general problem concerning the dimensions of the spectrograph room is following: The spectral lines with the shortest wavelength have always the longest focal lengths of camera mirror. They have also the smallest diffraction angle. That means that the spectral lines with the longest focal length are always in the same direction of the short part of the spectrograph room. One possibility to solve the problem of the different focal lengths could be the *Kutter*- system, as described in [4].

4.3 Case of Richardson Grating

Due to the many problems with the existing grating we suggest to choose another grating as an alternative one, as in [2]. We choose following grating:

- Richardson, plane, replica
- the blaze angle of the diffraction grating ϕ=17.5°
- the width of the diffraction grating W=206 mm
- the height of the diffraction grating H=154 mm
- number of grooves per mm C=1200 mm^{-1}

With this grating it is possible to work in the first spectral order. On one hand because of this case we have well distributed spectral lines. On the other hand we have a degradation of the chromatic resolution due to working in the first order. But this effect is compensated by increasing the number of grooves per mm. At Fig.4 one can see the well-distributed diffraction angles. It would be possible to have all the camera-objectives on one table. That means that we can use the calculated and optimated focal lengths of the camera mirrors.

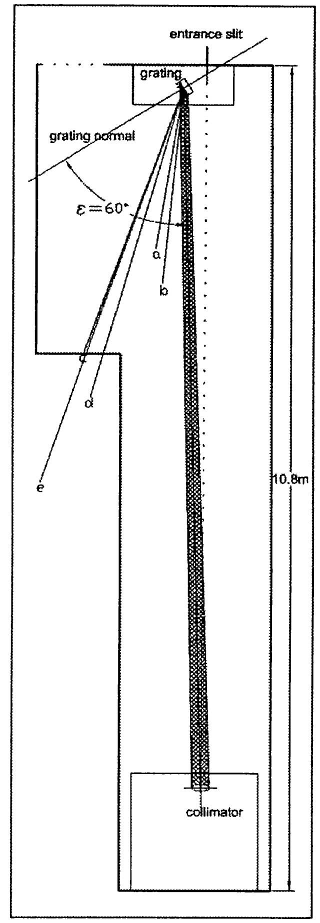

Fig. 3. Distribution of diffraction angles α in the spectrograph room for ε = 60°.

The intensity and the spectral order in the selected lines are as follows:

segment	spectral line	intensity [%]	spectral order n
a	Ca IR	43.50	1
b	Hα	79.53	1
c	D3	91.86	1
d	Hβ	99.67	1
e	CaK	76.14	1

The grating luminosity will be much better: cosε=cos15°=0.97

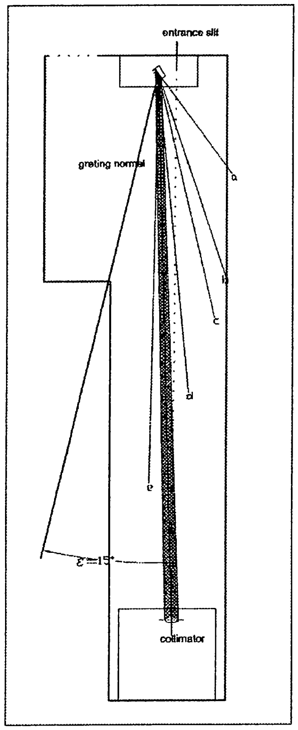

Fig. 4. Distribution of diffraction angles α for Richardson grating for $\varepsilon = 15°$.

4.4 Case of Echelle Grating

With Echelle grating it is possible to work in higher orders n>20. As already explained all the diffractions angles will be only in a small interval. We choose an Echelle grating with following parameters:

- the blaze angle of the diffraction grating ϕ=45.0°
- the width of the diffraction grating W=200 mm
- number of grooves per mm C=75 mm^{-1}

We have a degradation of the chromatic resolution because of the small number of grooves per mm. But this effect is compensated by increasing the spectral order n. At Fig.5 one can see that all the diffraction angles are in nearly of the same direction. This problem would be solved by a prisma and several spectras will be dispersed in sagittal direction. Then it will be possible to put the cameras in vertical direction one above the other. The intensity and the spectral order in the selected lines are as follows:

spectral line	intensity [%]	spectral order n
Ca IR	97.73	22
Hα	58.11	29
D3	96.50	32
Hβ	70.55	39
CaK	94.24	48

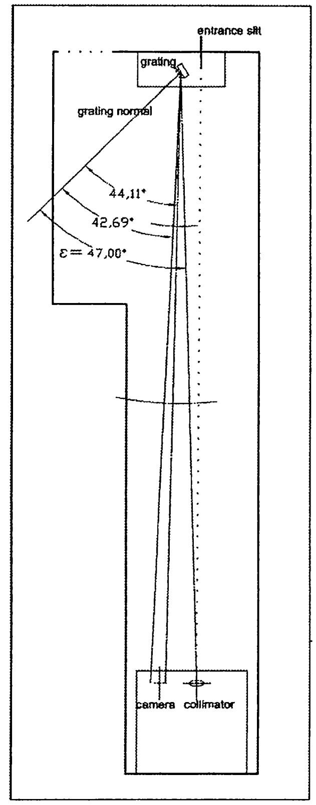

Fig. 5. Distribution of diffraction angles α for Echelle grating for $\varepsilon = 47°$.

5. ACKNOWLEDGEMENTS

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