OPTICAL DESIGNS OF PLANE ASPHERIZED GRATING SPECTROGRAPHS

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ABSTRACT: Spectrographs using plane aspherized gratings have excellent resolution over a wide field and require one less element than a conventional Schmidt or Maksutov camera. However, they are restricted to configurations where the grating is approximately normal to the camera axis.

1. INTRODUCTION AND SUMMARY

The construction of a plane aspherized grating spectrograph for the Canada-France-Hawaii Telescope was first proposed in a report evaluating the performances of 16 different spectrograph designs (Richardson, 1975).

Previous CFHT proposals for spectrographs with very few elements had all involved concave gratings. Perhaps the reason that a plane aspherized grating spectrograph had not been proposed earlier was that it was expected that it would suffer from axial astigmatism because of the high incidence angle, assuming that the aspherization were circularly symmetric. Once it was established that axial astigmatism was not a problem, there was renewed interest in the design and G. Lemaitre began making aspherized gratings for the CFHT using his elastic deformation techniques described in the next paper.

The advantages of the aspherized grating spectrograph are that it suffers less light loss because it has one less element compared with, say, a once-through Schmidt, and has better resolution over a wider field when used without a field flattener. Its disadvantages are that it requires special gratings and, because the axis of the camera must be approximately normal to the grating surface for best performance, it is much more limited in its selections of dispersions; finally, its resolution over a flattened field, using a multi-element lens, is not quite as good as a spectrograph using a once-through Schmidt plate and plane gratings. The latter Schmidt type was chosen for a general-purpose spectrograph for the CFHT and the aspherized grating spectro-

C. M. Humphries (ed.), Instrumentation for Astronomy with Large Optical Telescopes, 129–136.

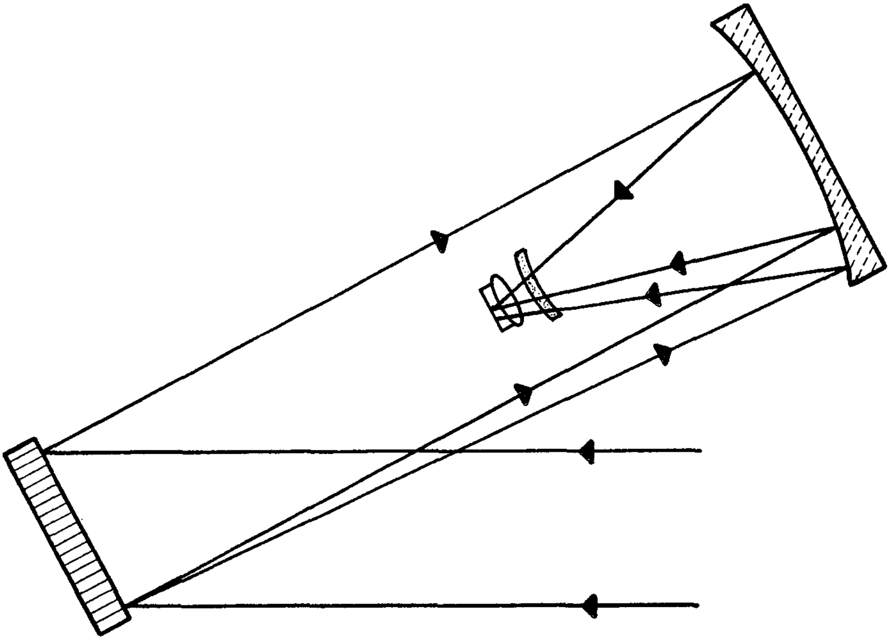

Figure 1. Aspherized grating spectrograph with doublet field flattener and image tube faceplate (collimator mirror not shown).

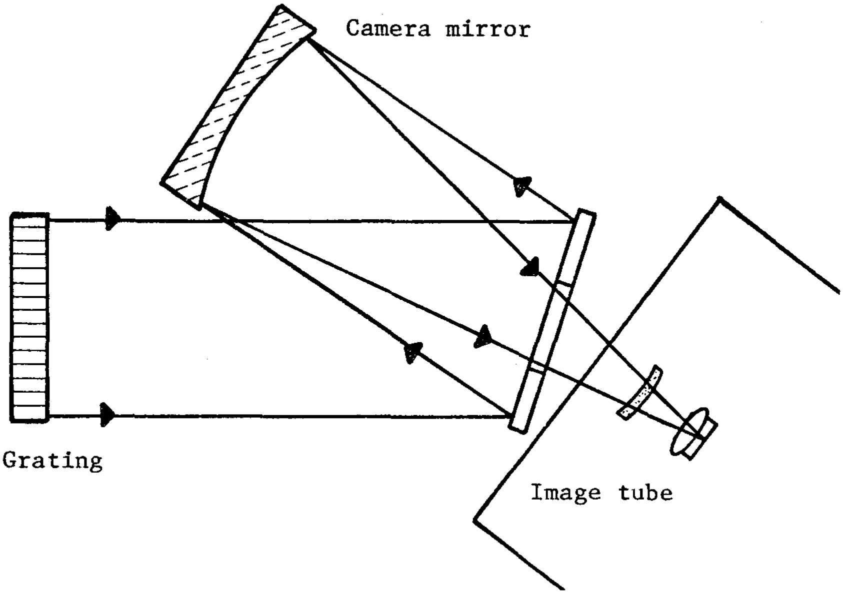

Figure 2. Aspherized grating spectrograph with folding flat and standard ITT magnetically focused tube; direction of dispersion perpendicular to plane of paper.

graph chosen as a specialized instrument.

The optical parameters given below were selected from the 1975 report referred to above. The optimizations were carried out assuming a square entrance aperture which is needed for the most efficient use of superpositioning-type image slicers (Richardson et al., 1971). The nominal focal ratio of the camera was chosen to be F/2 because this, or longer, focal ratios permit use with electronic detectors by either folding the camera or inserting a diagonal mirror.

A plane aspherized transmission grating spectrograph gives good results at low dispersions and has the aspherization on the back of the blank rather than on the ruled surface.

2. PLANE ASPHERIZED REFLECTION GRATING

Of the designs studied having F/2 cameras, the best uses an aspherized plane grating, that is, a grating ruled on a blank which departs slightly from its tangent plane: the rulings when projected onto the tangent plane are of constant spacing. The aspherized grating balances the spherical aberration of the camera mirror and no large lenses are required such as Schmidt or Maksutov corrector lenses. The layout (Figure 1) can consist merely of slit, collimator mirror, grating, camera mirror, curved focal surface. In this simple arrangement, the resolution is excellent over an exceptionally wide field of 13 degrees or more (by comparison, some modern stellar spectrographs have 7 degree fields). A version with a doublet field flattener lens has a 10 degree field and acceptable resolution. For use with large detectors, a holed folding flat can be used as is done in the well known folded Schmidt cameras (Figure 2).

This design resembles a twice-through Schmidt spectrograph but without the Schmidt corrector plate and with the grating aspherized instead. The optical aberrations are smaller than for the twice-through Schmidt and it is also better than the once-through Schmidt if the grating is approximately normal to the camera axis, with no field flattener lens.

Optical parameters of some spectrographs of this type are given in Table 1, for a 1200 g/mm grating in the 1st order blue, or a 600 g/mm in the 2nd order. Design No. 1 is optimized for use without a field flattener lens. Using a square entrance aperture (for image slicers) all of the 36 rays traced fall within 10 microns at the edge of a 10 degree field, i.e., at 3274 A and 4726 A with 4000 A at its centre. Most of this blur is caused by rays from the corners of the square aperture and if these four rays are omitted the remaining 89% of the rays fall within 4 microns, which is an indication of the resolution with a circular entrance aperture for use when image slicers are not used. On the grating, the diameter of the zero-power zone of the aspheric surface is 118mm which is approximately the diameter of

Collimator: paraboloid of radius to match telescope
Aspherized Grating: 600 g/mm
Angle of Incidence: 28.68 degrees
Angle of Diffraction: 0.0 at 4000 Å central wavelength, 2nd order

Design No.	Spectrograph Features	Element	Radius of Curvature and (Asphericities)*	Distance to Next Surface	Material to Next Surface	Clear Aperture (Y x X)
1)	No Field Flattener	Grating	34626. (A_a = -.195 E-08) (A_b = -.24 E-13)	400	air	102 x 116
	41 Å/mm at F/1.8	Camera Mirror	-400.	-197.79	air	109 x 210
		Focal Surface	-200.			6 x 48
2)	With Field Flattener	Grating	18045. (A_a = -.167 E-08) (A_b = -.13 E-13)	400.	air	102 x 116
	42 Å/mm at F/1.7	Camera Mirror	-400.	-182.00	air	109 x 182
		First Field Flattener Lens	126.83 215.18	-6. -2.01	fused silica air	16 x 50
		2nd FF Lens	-69.13 112.17 (A_b = -.11 E-08)	-5.93 -0.05	f.s. air	11 x 43
		Window tilt = 0.13°	∞	-5.3	f.s.	6 x 35
		Focal Surface	∞			
3)	Field Flattener Removed & Camera Aspherized	Grating	Same as (2) above			102 x 116
		Camera Mirror	-429.89 (CC = -1) (A_a = -.167 E-08) (A_b = -.68 E-14)	-210.06	air	109 x 210
	38 Å/mm at F/1.9	Focal Surface	-278.78			6 x 48

*Equation of surface:

$$Z = \frac{x^2}{R\left(1+\sqrt{1-(CC+1)\frac{x^2}{R^2}}\right)} + A_a x^4 + A_b x^6$$

CC = Conic Constant = -(eccentricity)^2 A_a + A_b are aspheric coefficients
R = radius of curvature

Table 1. Aspherized Reflection Grating Spectrograph

the entrance aperture divided by the cosine of the angle of incidence.

This superb resolution suggests that satisfactory results could be obtained if the focal ratio of the camera were reduced from F/2 to F/1.0. However, the smaller focal ratio cameras have larger central obstructions when the light is reflected into image tubes which are too large to be located on axis, i.e., other than diode arrays.

Design No. 2 in Table 1 is optimized for use with a doublet field flattener lens followed by a window of an image tube. For a circular aperture, the image size ranges from 2 to 16 microns over a 10 degree field, and to 26 microns for a square aperture which is satisfactory. In this optimization, the diameter of the 0-power zone increases to 145mm. Further improvements can be made to the field flattener design.

Better resolution results if the tube window is omitted. One could use a singlet field flattener lens but, as with a Schmidt spectrograph, it causes coma which is minimized if the lens is thin, which is not possible when an image tube window is introduced which effectively thickens the lens. The purpose of the additional lens (the first one) is to eliminate the coma.

A disadvantage of the aspherized grating design is that the resolution is not as good if the angle of diffraction of the central wavelength is not zero, as must be the case for low dispersion gratings whose angles of incidence are smaller than the minimum angle between the camera and collimator axes. However, the resolution is satisfactory for the 10cm gratings. A 300 g/mm grating gives 160 A/mm dispersion. Of course, gratings giving dispersions intermediate between 40 A/mm and 160 A/mm can also be used.

For use with large detectors, the camera is folded as shown in Figure 2 and as is done in the well-known Schmidt cameras. The area of the hole in the folding mirror depends on the location of the photocathode of the image tube. Thus, some image tubes can have a folding mirror with a hole much smaller than that shown, which is for an off-the-shelf magnetically focussed ITT tube with the magnet mounted behind the mirror. In this bad case, the area of the hole is 37% of the area of the aperture. The area of the hole could be reduced if a magnet for a larger tube were used so that the folding mirror could be located inside the magnet. In the case of the Spectracon electronographic tube, its 30mm photocathode is closer to the end of the magnet and the hole need be only 14% of the beam and at the CFHT Cassegrain focus, virtually nothing is added by the hole to the shadow already produced by the secondary mirror of the telescope.

The grating asphericity is different for Designs (1) and (2) of Table 1, but is the same for Design (2) and Design (3). The latter does not have a field flattener and the camera mirror is aspherized. The results are as good as for Design (1) and even for the edge of a 13.8 degree field (3000 A and 5000 A) the images are 22 microns for a square aperture and 12 microns for 89% of the rays. Thus, it is not necessary to change the grating when the field flattener is removed, but it is necessary to change the camera mirror which could be cheaper than an aspherized grating.

A dispersion of 20 A/mm is achieved using a 1800 g/mm grating in the 1st order with a camera mirror of f/1.9 (parallel to dispersion). The length of the grating rulings is 100mm and the width of the ruled area is 145mm, the angle of incidence being 46 degrees with zero-angle of diffraction at the central wavelength of 4000 A. The diameter of the 0-power zone is 147mm which is approximately the length of the rulings divided by the cosine of the angle of incidence, i.e., 100/cos46 (the focal ratio perpendicular to the dispersion is F/2.8). The optical parameters are given in Table 2. The radius of curvature of the focal surface is 277mm and even for a square aperture collimator the resolution is superb over a 10 degree field, being 5 microns; and the resolution is 23 microns at the ends of the very large 20.7 degree field (101mm) covering the spectral region from 3000 A to 5000 A at 20 A/mm.

If the focal ratio (in the direction of dispersion) is relaxed to f/2.8, the dispersion becomes 13.8 A/mm and the resolution improves to 11 microns at the ends of the 20.7 degree (145mm) field. The use of a field flattener lens will degrade the resolution if a simple lens is used. However, a triplet lens with an aspherized camera mirror and the unchanged grating produces very good resolution, being better than 20 microns for 89% of the rays in a square aperture over the 20 degree (100mm) flat field for the f/1.9 camera.

It is preferable to have the fibre optic faceplates of image tubes curved to match the natural field curvature of the spectrographs with folded cameras. The field is curved in the same sense as the photocathode curvature of electrostatically focussed tubes. Curving the fibre optic faceplate decreases the variation of thickness from centre to edge and also eliminates the need of a field flattener. Such curved fibre-optic faceplates can be obtained on special order.

Even better would be to have the electron optics of the sensor designed so that the photocathode curvature matches the field curvature of the spectrograph, thus eliminating the disadvantages of having either a fibre optic or a field flattener lens in the system.

3. TRANSMISSION GRATING SPECTROGRAPHS

Low dispersion transmission gratings have very good blaze efficiencies, and can be located at the centre of curvature of the camera mirror if the grating is replicated onto a Schmidt plate. A 300 g/mm 1st order plane transmission grating f/2 spectrograph has a dispersion of 166 A/mm and its field covers the region from 3000 A to 9000 A. Optical parameters are given in Table 3. For a square aperture, 100%

Angle of Incidence: 46°
Central wavelength 4000 Å
Dispersion: 20 Å/mm
Field: 20 degrees: 3000 Å to 5000 Å

Element	Radius of Curvature (Asphericities)	Distance to Next Surface	Medium to Next Surface	Aperture
Grating (Reflection)	37172.4 (A_a = -.813 E-09) (A_b = -.55 E-14)	552.40	Air	100 x 145
Camera Mirror	-552.44	-272.68	Air	100 x 236
Focal Surface	-276.99			3 x 101

Table 2. 1800 g/mm Aspherized Grating Spectrograph

	Radius of Curvature & (Asphericities)	Distance to Next Surface	Material to Next Surface
Back of Grating Blank with Schmidt Correction	12796.27 (A_a = 0.780 E-08) (A_b = -.97 E-13)	16.0	Fused Silica
Grating Resin		$\sim$0.02	Resin
Grating decentered 2 mm		400.27	Air
Camera Mirror	-400.0	-198.48	Air
Focal Surface	-196.56		

Table 3. 300 g/mm Transmission Grating Spectrograph (1st order)

of the rays fall within 38 microns and 89% within 14 microns and the corresponding figures are 17 microns and 5 microns at 3500 Å, 1.3 microns and 1 micron at 4000 Å, 16 microns and 7 microns at 5000 Å, 28 microns and 11 microns at 6500 Å, and 33 microns and 15 microns at 9000 Å.

Unlike the aspherized reflection grating, the transmission grating does not require a special ruling because it can be replicated from existing masters onto the flat side of the Schmidt plate.

4. COMPARISON OF ASPHERIZED AND VARIABLE SPACING (HOLOGRAPHIC) GRATINGS

An alternative to an aspherized grating is a flat grating with a groove spacing varying across the grating to correct the spherical aberration of the camera mirror. The layout could be the same as shown in Figure 1 and excellent resolution occurs at the centre of the field. However, the resolution at the edge of the field is poor, being about 60 microns compared with 4 microns for the aspherized grating.

In both cases the grating is designed to correct the spherical aberration at the centre of the field and is therefore incorrect elsewhere. However, the error in correction at the edge of the field is approximately proportional to the difference in dispersion between centre and edge for the aspherized grating which can be very small if the angle of diffraction is small, the dispersion being proportional to the cosine of the angle of diffraction, β. On the other hand, the error for the variable spacing grating is proportional to the difference in wavelength between the centre and edge of the field which is considerable, being approximately proportional to the difference in $\sin\beta$ between the centre and edge. The grating equation and derivatives are as follows:

$$n\lambda = a(\sin\alpha + \sin\beta)$$

where n = order of diffraction, a = groove spacing, λ = wavelength, α = angle of incidence and β_o, β_1 = angles of diffraction at centre and edge of field, respectively.

For a variable spacing grating, $\Delta a = (-a^2/n\lambda)\cos\beta_o \cdot \Delta\beta$ and the error at the edge of the field is

$$\Delta(\Delta\beta) = \frac{n}{a^2}\left\{\frac{\lambda_1}{\cos\beta_1} - \frac{\lambda_o}{\cos\beta_o}\right\}\Delta\alpha \simeq \frac{n}{a^2\cos\beta}(\sin\beta_1 - \sin\beta_o)$$

which is considerable. For the aspherized grating which has a variable angle of incidence and an approximately constant spacing, $\Delta\alpha = (\cos\beta_o / \cos\alpha_o)\,\Delta\beta$, and the error is

$$\Delta(\Delta\beta) = \cos\alpha_o\,(1/\cos\beta_o - 1/\cos\beta_1)\,\Delta\alpha$$

which is small.

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