The design of dispersing elements for a highly segmented, very wide-field spectrograph

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\textbf{ABSTRACT}

Wide field spectrograph at the largest optical telescopes will be decisive to address the main open questions in modern astrophysics. The key feature of this instrument is the modular concept: the spectrograph is the combination of about one thousand identical small cameras, each carrying a few slits and operating at low to moderate spectral resolution, to be illuminated at the Cassegrain focus of an existing 8m class telescope. The dispersing element to be used in these small cameras has to satisfy some requirements in term of efficiency, resolution, size, small series production. Moreover the cameras have to work both in imaging and spectroscopy modes, therefore a GRISM configuration of the dispersing element is suitable. Based on these considerations, we have focused our attention to Volume Phase Holographic Gratings (VPHGs) since they show large peak efficiency in the target spectral range (400-800 nm), they can be arranged in a GRISM configuration reaching relative large resolution. The main constrains concern the available room for the dispersing element, indeed the camera design is very compact. As a consequence, slanted VPHGs are studied and optimized in combination with normal and Fresnel prisms.

**Keywords:** VPHG, dispersing element, Fresnel prism, GRISM, spectroscopy

\section{INTRODUCTION}

It is generally believed that very fast cameras imaging large Fields of Views (FoV) translate into huge optomechanics and mosaics of very large contiguous CCDs. The concept here is the building of a mosaic of “Smart Fast Cameras”, designed to have low weight and size with respect to any focal reducer or prime focus station of the same performance, which can be applied to existing 8m-class telescopes to provide a wide field fast focal plane. Placed on aberrated Field of Views, including those of slow focal ratios, it is able to provide imaging at an equivalent focal ratio as low as F/1, with a size that is identical to the large focal ratio of the focal plane. The design allows for easy correction of aberrations over the Field of View. Preliminary optical designs show that a trapped Cassegrain option allows for a useful Field of View as large as three degrees in diameter.

This kind of instrument represents, an important opportunity to boost the capability of an existing 8m class telescope in the time framework 2015-2020 prior to the EELT appearance on the international scene.

The key feature of this instrument is the modular concept: the spectrograph is the combination of about one thousand identical small cameras, each carrying a few slits and operating at low to moderate spectral resolution, to be illuminated at the Cassegrain focus of an existing 8m class telescope. As shown in figure 1, the basic principle is to replicate a relatively small FoV focal reducer on a bi-dimensional matrix, eventually allowing one to cover a much larger FoV. The replicas are identical, other than for the aberration compensation plates that depend upon the position in the telescope.

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One can cover the FoV with an array of almost identical lenslet focal reducers (see figure 1 on the right). The lenslet focal reducers differ only in the type of pupil plane aberration corrector chosen that is a function of focal plane radial position only. If one allows the focal surface to be curved, substantial simplification of the lenslet optics are possible.

![Figure 1. On the left, an overall layout of the camera composed by a large number (e.g. one thousands) of small units mounted on a single derotated frame. On the right, A schematic view of a single unit. An intermediate focal plane at F/3 allows for placing multiple slits. The two pupil planes allow for aberrations compensations and for insertion of a dispersing element.](image)

The image, with large plate-scale (hence physically large) formed in the focal plane is segmented by the array of lenslets, each a very few arcmin square. An array of aberration correctors are placed in the pupil plane, each correcting the approximately constant aberrations found across the FoV of each lenslet system. Finally an array of camera lenses produces an array of images detected by the CCDs, with a much more user-friendly plate-scale. Whenever the aberration on the long focal plane is large, objects imaged on the edges between two adjacent lenslets will be shared between the corresponding detectors. Therefore it is suggested that the size of the latter element should be enlarged with respect to the nominal one by the largest spot aberration so that no light loss occurs, other than losses due to the imperfections of the lenslet edges. This will result in a small overlap of adjacent parts of the FoV.

### 2. REQUIREMENTS AND CONSTRAINS

Starting from the description of the instrumentation, we are in the position to give the requirements of the dispersing elements suitable for having the expected performances. Table 1 summarizes the parameters and requirements used to perform the analysis:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation mode</td>
<td>Imaging/spectroscopy</td>
</tr>
<tr>
<td>Telescope Diameter (D_T), F#</td>
<td>8200 mm, F/2</td>
</tr>
<tr>
<td>Size of camera collimated beam</td>
<td>15 mm</td>
</tr>
<tr>
<td>Spectral range</td>
<td>400 – 800 nm</td>
</tr>
<tr>
<td>Undeviated wavelength</td>
<td>600 nm</td>
</tr>
<tr>
<td>Resolving Power (1 arcsec slit)</td>
<td>&gt;200</td>
</tr>
<tr>
<td>Peak efficiency (only grating)</td>
<td>&gt;85%</td>
</tr>
<tr>
<td>Minimum efficiency in the spectral range</td>
<td>&gt;45%</td>
</tr>
</tbody>
</table>

Table 1. Parameters of the instrumentation used to design the dispersing elements.

First of all, the cameras will work in imaging and spectroscopy mode and the layout is a classical focal reducer. It is apparent that they requires, as dispersing element, a combination of a grating and prisms in a GRISM configuration.
Since the number of cameras is huge and the available room is limited (the cameras are closed together for covering the FoV), also the size of the dispersing element is limited. Moreover, it will be tricky the moving of the dispersing element inside and outside the collimated beam to perform spectroscopy and imaging.

Another important issue is the resolution of the camera, indeed the combination of large telescope and small camera generally turns into a very low resolution regime (as will be explain later).

Due to the large number of identical cameras, the technologies used to make the dispersing elements, as well as the other opto-mechanical components, must be suitable for large production.

3. PROPERTIES OF THE DISPERSING ELEMENT – VPHG

As dispersing elements we focused our attention to Volume Phase Holographic Gratings (VPHGs) where the diffraction is achieved thanks to a periodic modulation of the refractive index in the volume of the grating. They are becoming more and more popular in astronomical instrumentations because of some interesting features, in particular:

- The peak efficiency can be theoretically 100% and usually value of the order of 90% are obtained;
- The efficiency curve can be tune in wavelength by changing the incident angle, allowing to cover a wide range of wavelengths with very high efficiencies;
- The devices are robust since the active material is usually embedded in between two glass windows;
- Large VPHGs can be produced if a big holograph is available meeting the requests for example of astronomical instrumentation attached to big telescopes;
- Line densities up to 6000 l/mm can be achieved allowing to make high dispersing devices;
- The device is easily customizable.

Moreover the production of VPHG in spite of the fact that the gratings are always “master” is well established and mass production is possible.

The dispersion features of a VPHG are exactly the same of the surface relief gratings (SRGs), indeed the diffraction obeys to the well know grating equation:

\[ m\lambda G = n(\sin \alpha + \sin \beta) \]  

Where \( m \) is the order of diffraction, \( G \) is the line density, \( \lambda \) the wavelength, \( \alpha \) and \( \beta \) the incidence and diffraction angles respectively and \( n \) the refractive index of the medium.

Completely different is the VPHG behavior in terms of diffraction efficiency compared to the SRG. Indeed as already hinted before the efficiency curve changes by changing the incident angle as clearly shown by the efficiencies measured for a 990 l/mm VPHG:

![Efficiency curves at different incidence angles for a VPHG](image-url)
The efficiency is large when the Bragg condition is satisfied ($\alpha = \beta$). From the material point of view, the efficiency is driven by the thickness of the active layer ($d$) and by the modulation of the refractive index ($\Delta n$)\textsuperscript{17}.

An important possibility provided by the VPHGs is the slanting angle of the fringes (figure 3), namely the fringes are tilted of a specific angle ($\psi$) in respect to the grating normal:

![Figure 3. Scheme of a standard VPHG (on the left) and of a slanted VPHG (on the right) ](http://proceedings.spiedigitallibrary.org/)

Up to now there are few applications of slanted VPHGs\textsuperscript{18,19}, but potentially they are interesting, for example, in making simpler GRISM (as we will show later) and because it is possible to achieve the Bragg condition enter normally to the grating surface. On the other hand it is more difficult to design the gratings since the diffraction conditions depend on the average refractive index of the active material, which is not easily know and it varies depending on its modulation.

Focusing the attention to the resolving power (resolution) $R$ of the dispersing element, the maximum theoretical resolution achievable for a grating with line density $G$ is\textsuperscript{15}:

$$R = \frac{\lambda}{\Delta \lambda} = mGL$$

(2)

Where $L$ is the illuminated length of the grating. Just from this equation it is clear that a large resolution can be obtained by increasing the size of the grating and/or the line density. In our case the length is limited by the size of the small cameras, therefore we will have to play with the line density (working at the first diffraction order).

The actual resolution of the spectrograph is smaller than the theoretical one, because of the finite size of the object (determined in this case by the slits), therefore it depends on the optical characteristics of the telescope and the camera. In particular the resolution can be expressed as follow\textsuperscript{20}:

$$R = \frac{mGL\lambda}{\chi D_T}$$

(3)

Where $D_T$ is the telescope diameter and $\chi$ is the angular slit width. In this analysis, as usual, the slit width is fixed to 1 arcsec. We can easily understand that large resolution can be obtained for large telescopes ($D_T$) only if the grating is big ($L$) and consequently the instrumentation is big. This is not our case, because of the segmentation of the focal plane with many small cameras.
4. CONFIGURATIONS

According to the optical layout of the camera reported in figure 1, as already pointed out, the dispersing element of choice is a GRISM. In the case of VPHG usually two prisms are required. The role of the first prism is the bending of the beam in order to enter in the grating with a defined angle, the role of the second one brings back the beam to the camera direction. By using a slanted VPHG only one prism is required, since the slanting angle plays the role of the other one (which can be either the entrance or exit one).

As already pointed out a constrain is the available room for the grism in the camera. Indeed this limit not only the size of the grating, but also the maximum angle of the prisms. Moreover the grating substrate has a thickness of 2-3 mm in order to maintain a good surface quality and the prism edges must be cut in order to reduce its brittleness. The dimensions (in mm) of the GRISMS are summarized in the scheme reported in table 1. In the table the different configuration are reported together with the prism apex angle. Indeed this angle is a key parameter of the GRISM, since it determines the incidence angle on the grating and knowing the undeviated wavelength, it determines the line density of the grating.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Prism apex angle $\phi$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Substrate thickness 2 mm</td>
</tr>
<tr>
<td>Prism edges =&gt;</td>
<td>1mm</td>
</tr>
<tr>
<td></td>
<td>16.65</td>
</tr>
<tr>
<td></td>
<td>19.19</td>
</tr>
<tr>
<td></td>
<td>35.20</td>
</tr>
</tbody>
</table>

Table 2. Different configurations of the dispersing element and the maximum prism apex angle ($\phi$). The scheme reports the maximum dimensions (in mm) according to the preliminary optical design.
Due to the extremely small dimensions of the GRISMS, also the thickness of the VPHG substrate affects the prism angle.

The first and the second configuration are similar, the only difference consists in the possibility to glue the second prism directly on the gelatin layer. This is feasible especially in this case, since the size of the elements is small. Indeed, the gluing process is tricky and it is really risky if the size and cost of the prisms are large.

This allows to noticeably increase the apex angle of the prism and consequently to increase the line density of the grating. Moreover, reducing the number of glass components to be coupled, it is possible to reduce the reflections losses (and ghosts). The problem becomes more important if the refractive index of the glass for prims is different from the refractive index of the grating.

The third configuration is very difficult to obtain, since it requires the deposition of the active material (usually dichromated gelatin, DCG) directly on the prism surface and the consequence exposure and development.

The last configuration requires the use of slanted VPHG. In this case the maximum apex angle remarkably increases, but the presence of the slanting angle turns into a larger diffraction angle \( \beta \) compared to the unslanted grating and consequently a larger apex angle is required for the same dispersing conditions. This is due to the need of compensation not only of the diffraction angle, but also of the slanting angle.

RESOLUTION

According to table 1 and equation 3, we can calculate the \( R_s \) (the resolving power for a 1 arcsec slit) of the GRISM as function of the prism apex angle \( \phi \) and refractive index for the undeviated wavelength (600 nm). It is apparent from equation 1, that the prism features are dependent on the line density of the grating and vice versa.

\[
R_s = \text{function of } \phi, \text{ line density, and refractive index.}
\]

![Graph](image1)

Figure 4. Resolving Power as function of the refractive index and apex angle of the prism; on the right the corresponding line density.

How expected, the resolution is small because of the small dimension of the grating. The use of high refractive index glasses can help, but it increase the cost of the prisms. As for the line density, the parameter falls in a common realization window for VPHGs.

A possible solution to overcome the issue related to the angle of the prism is the use of Fresnel prisms which consist of an array of small prisms (figure 5). Likewise the Fresnel lenses, here the bulk material is removed and it remains only the shape of the optical element:
With these elements, it is possible to reach high apex angles without increasing the overall thickness of the element. On the other hand the structure is not 100% efficient due to multiple internal reflection or total reflections. Fresnel prisms can be coupled with slanted VPHGs obtaining the most compact dispersing device for our instrumentation. The most important point is the optical quality of such prisms and the resulting quality on the detector focal plane. It is clear that Fresnel prisms can be coupled also with unslanted VPHGs providing a more compact GRISM.

We perform theoretical calculations based on RCWA approach\(^{21,22}\) in order to maximize the efficiency of the grating by acting on the material parameters (thickness and refractive index modulation of the gelatine layer). Two cases are discussed, the first one related to the configuration 2 in table 2 and the second related to configuration 4. For the analysis we considered the average refractive index of the active layer equal to 1.4 and we neglected the reflection losses. Moreover the incidence angle (and consequently the prism apex angle and refractive index) is chosen to satisfied the Bragg condition for a wavelength of 600 nm.

**EFFICIENCY**

**CASE 1.**

We consider an apex angle of the prism closed to the maximum made of a medium refractive index glass. This case is on the lower limit in terms of resolution, but it is still useful to understand the possibility of VPHG.

- Prism angle = 20°
- Rs = 201
- \( n_{\text{prism}} = 1.7 \)
- \( \frac{d\lambda}{dx} \approx 37.8 \text{ nm/mm (on the detector)} \)
- Line density = 817 l/mm
- Spectral dimension (400-800 nm) \( \approx 10.6 \text{ mm} \)

The peak efficiency is reported in figure 6 as function of the modulation of the refractive index and the thickness of the gelatin layer.
Figure 6. Efficiency map for the grating with 827 l/mm as function of $d$ and $\Delta n$. On the right two efficiency curves for an incidence angle in Bragg at 600 nm.

The efficiency reaches values closed to 100%, but this is not the only parameter we are interested in. Indeed it is important to have also a wide efficiency curve in order to cover the whole spectral range efficiently. Focusing the optimization in the region of large peak efficiency it is clear that different couples $d$–$\Delta n$ provide completely different efficiency curves. Case B is more suitable since the curve is flatter with an efficiency above 50% at the limits of the spectral range and a peak efficiency larger than 90%.

CASE 2.

Here we consider the use of Fresnel prisms (made of BK7 glass) and a slanted VPHG. Only one prism is needed with a large apex angle (59° in this case), here it is reported the equivalent angle in the case of standard GRISM.

Equivalent prism angle = 33°

Rs = 296

$n_{\text{prism}} = 1.516$ (BK7)

$d\lambda/dx \cong 27.5 \text{ nm/mm}$ (on the detector)

Line density = 1046 l/mm

Spectral dimension (400-800 nm) $\cong 14.5$ mm

Slanting angle = 12.6°

Figure 7. Efficiency map for the slanted grating with 1046 l/mm as function of $d$ and $\Delta n$. On the right two efficiency curves for an incidence angle in Bragg at 600 nm.
In the same way of case 1, the curves can be different with similar peak efficiency, by performing a more careful optimization, we can achieve the following curves (figure 8):

![Efficiency curves](image)

Figure 8. Efficiency curves of the first and second orders for the slanted grating at an incidence angle in Bragg at 600 nm.

The efficiency curve is really sensitive to small changes of the grating parameters. By reducing the thickness, the efficiency at 400 and 800 nm reaches 50% with a peak efficiency closed to 90%. It is apparent that this combination shows interesting advantages. First of all, the small number of optical elements to be coupled (only a grating and a prism); secondly, the resolution achieved is closed to 300.

5. CONCLUSIONS

Very wide-field spectrograph made of a matrix of small cameras is an interesting approach for instrumentation of 8-m telescopes (and also smaller). The design of the dispersing element is not trivial, because of different constrains, mainly related to the limited space available and to the large ratio between the telescope diameter and the camera diameter which affects the resolution. Here we focused the attention to VPHG solution coupled with prisms in a GRISM configuration. The analysis showed that the apex angle of the prism is limited and consequently the line density of the grating. A solution with slanted VPHG coupled with a Fresnel prism is the most compact solution with the smallest number of optical elements. The resolution is approximately 300 by choosing the grating with a line density of slightly larger than 1000 l/mm. It will be important to evaluate the quality of the Fresnel prisms for astronomical instrumentation in terms of optical quality.

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REFERENCES


