Design, calibration and assembly of an Offner imaging spectrometer

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Abstract. We present a rapid and efficient method of design, assembly and calibration of an Offner dispersive imaging spectrometer. Experimental results are described from a laboratory prototype that was built adapting an analytic model to an experimental design. This imaging spectrometer has a spectral range from 400 nm to 1000 nm, 245 spectral bands and an f number of 2.4. Therefore, this work allows high optical quality and low cost imaging spectrometers to be built.

1. Introduction

A conventional RGB photography gives information about a scene in three wide spectral bands thus providing limited spectral information for each point on the scene. On the other hand, a hyperspectral sensor or imaging spectrometer is a device that collects spectral information in hundreds of contiguous and closely spectral bands.

Hyperspectral imagers have many applications in several areas such as agriculture, geology, oceanography, forestry, medicine, colorimetry, security, military and others. They are applied to perform many different tasks such as clinical diagnosis imaging, object identification, target detection, process control and environment assessment [1] [2].

The hyperspectral imagers can be classified depending on the image acquisition modes (whiskbroom, pushbroom, framing or windowing) or the method used for spectral processing (dispersion elements, filter-based systems or Fourier transform spectrometers) [3]. In this paper we present the design, assembly and calibration of an Offner spectrometer, which is of dispersive and pushbroom type. Pushbroom imagers scan the sample through a slit so the image is processed stripe by stripe. Dispersive spectrometers use dispersion elements (gratings or prisms) to separate the incoming electromagnetic radiation into different angles, thus the spectrum is focused at distinct locations of one dimension of the detector array.

A standard Offner imaging spectrometer is made up of three spherical and concentric surfaces: two concave mirrors and a classical convex grating (equally spaced grooves) (Figure 1). For an optimized design, this system has a good resolution and low distortion in the spectral and spatial dimensions.
2. Design

A rapid and efficient analytical design has been used [4]. The procedure consists of the calculation of the intermediate images of the slit center produced by each element. The meridional and the sagittal images of an off-axis object point produced by a reflective spherical grating satisfy the following equations [4]:

\[
\frac{\cos^2 \theta}{r} + \frac{\cos^2 \theta'}{r'_M} = \frac{\cos \theta + \cos \theta'}{R} \quad (1)
\]

\[
\frac{1}{r} + \frac{1}{r'_S} = \frac{\cos \theta + \cos \theta'}{R} \quad (2)
\]

where \( \theta \) and \( \theta' \) are the incidence and diffraction angle given by the Bragg relation. \( R \) is the curvature radius of the grating and \( r \) and \( r'M_s \) are the distances from an object point and an image point to the incident point of the reference ray. The equations (1) and (2) are also applied to mirrors where \( \theta = \theta' \).

By applying these equations iteratively at each surface, meridional and sagittal curves are obtained in the whole spectral range. Making these curves tangent to each other for a given wavelength leads to cancellation of astigmatism and its spectral derivative at this wavelength. This results in a significant decrease in astigmatism for the entire spectrum. Furthermore, the slit center is located at the Rowland circle of the first concave mirror; this strategy assures a coma free image of the design point at any wavelength. It is to highlight that high quality images are obtained without use of non-spherical surfaces nor specific aberration corrected gratings, even for low f numbers.
Table 1. Characteristics and values of the components used in the prototype.

| Specifications         | Values                        |
|------------------------|-------------------------------|
| Spectral Range         | 400-1000 nm                   |
| f number               | 2.4                           |
| Image Size             | 8.8 mm x 6.24 mm (spectral dim) |
| Entrance Slit          | 20 µm x 10 mm                 |
| Concave mirror radius (1) | 135 mm                       |
| Grating radius (2)     | 70 mm                         |
| Grating groove density (2) | 150 lines/mm                 |
| Concave mirror radius (3) | 128 mm                       |

Based on the above considerations, it has been designed an Offner spectrometer in the VIS-NIR spectral band. At the time of assembling the laboratory prototype, it was noted that the radii of the purchased elements differed lightly from the initial design values, so the system had to be redesigned taking into account the new values. Final specifications are given in table 1. Figures 2 and 3 show the spot diagrams obtained by simulation of the initial design and the laboratory prototype. They correspond to three object points (on-axis, 0.7 and full field) at wavelengths of 0.4, 0.7 and 1 µm. These diagrams were built using the optical design software OSLO-EDU®.

3. Alignment and assembly
An He-Ne laser and a Michelson-Morley interferometer are used to achieve concentricity, as in reference [5]. Like in a common Michelson-Morley interferometer, a parallel beam of light comes from one of the arms of the interferometer. A converging lens is introduced in the other arm in order to focus the laser on an auxiliary plane grating which illuminates the concave mirrors with two of its diffraction orders. First, the zero diffracted order is used to place the auxiliary grating on the lens focus. In an arbitrary position, several fringes are seen at the interferometer output. On focus, the reflective beam emerges collimated from the lens minimizing the number of fringes. Next, the concave mirrors are positioned by using the grating’s first diffraction orders. In this case, minimization of
fringes is got when light reflected from the mirrors returns to the lens focus (see figure 4). Finally, the convex grating is positioned with the convergent beam coming directly from the lens.

![Figure 4](image-url)  
*Figure 4.* Alignment setup: A converging lens focus the laser on an auxiliary plane grating which illuminates the concave mirrors with two of its diffraction orders. The convex diffraction grating is positioned by illuminating it directly with the lens.

One important point is that the convex grating must remain as the system aperture stop. The convex grating is placed on a rotation stage so its center coincides with the grating curvature center. This system allows the rotation of the grating without losing concentricity. The center of the entrance slit is positioned using a micrometric travel platform from the common center of mirrors curvature to its final position. The entrance slit is placed in a rotation stage to realign the slit orientation and it keeps the slit and the spatial dimension of the CCD parallel.

Finally, the CCD is situated looking for a tiny image of the slit when it is illuminated with an He-Ne laser. The laser wavelength is close to the design wavelength (700 nm). Next, the slit is illuminated with Hg and Ar spectral lamps. These lamps are chosen because they cover the whole system spectral range. The CCD is lightly moved again to find a position with high spatial and spectral quality.

Photographs of the laboratory prototype are shown in figure 5. At right on the photographs, an objective lens from Schneider Optics with 17 mm focal distance images a scene on the spectrometer entrance slit. This lens is broadband coated and aberration corrected for the spectral range of 400-1000 nm. The entrance slit is an air slit fabricated on a metallic substrate, 20 mm wide and 10 mm long as specified in table 1. At left, the concave mirrors are mounted on XYZ translation stages. They are aluminum coated with radii as given in table 1 (±5 % tolerance) and their aperture diameter is 65 mm. The diffraction grating is a holographic grating with equally spaced grooves. Its groove density is 150 lines/mm, its radius of curvature is 70 mm and the aperture diameter is 29 mm. The grating is not very efficient in the m = -1 diffraction order, but it is sufficient for demonstration purposes. Translation and rotation mounts are used to precisely positioning of the grating. Just behind the grating, a metallic coated prism is used to fold the instrument in the image space. It allows allocating space to the image detector.
Figure 5. Top view (a) and side view (b) of the laboratory prototype. A Schneider refractive objective is used to image on the entrance slit.

4. Characterization and calibration
The CCD has 1392 x 1040 pixels (8.8 mm x 6.6 mm). The system is designed to expand the spectrum of an 8.8 mm entrance slit along 6.24 mm. Although the imaging spectrometer is ready to work with 4x4 binning mode, all the CCD pixels are used for the characterization and calibration (1392 x 980 pixels). The prototype is characterized using the Hg and Ar lamps and a white-light source. The spectral image and the spectrum of the slit center obtained when the slit is illuminated simultaneously with these lamps are shown in figures 6 and 7, respectively.

An important step of the calibration consists of relating the pixel position to the wavelength. The emission spectral lines of the Hg and Ar lamps are tabulated. In figure 8, the position of several known peaks is plotted against pixel position. This relation keeps linear along the whole spectral range.

Figure 6. Image of the spectrum obtained when the system is illuminated with lamps of Ar and Hg simultaneously.

Figure 7. Spectrum of the slit center corresponding to a centered vertical line in figure 6.
Choosing emission spectrally resolved peaks, the spectral resolution of the system is analyzed for different wavelengths and different heights of the slit. The first laboratory prototype achieves spectral resolutions better than 2 nm in the 400-1000 nm range. In order to analyze the spatial resolution, a secondary slit which is perpendicular to the entrance slit is illuminated with a white light source. The Schneider objective lens is used to image one slit into the other. A narrow line is shown in the CCD along the spectral dimension. Decreasing the width of the secondary slit and changing its position, the spatial resolution can be estimated for several heights of the entrance slit. When a 12 µm wide entrance slit was used, spatial resolutions better than 20 µm were found.

The pushbroom dispersive imaging spectrometers present some typical distortions in the image called smile and keystone [5]. Smile refers to the curvature of a spectral line (see figure 9). The change of magnification with position is called keystone. This non-linear behaviour can be observed creating a narrow line along the spectral dimension in different parts of the slit (such as it was explained for spatial resolution characterization). The experimental device shows a smile less than 6 µm and a keystone less than 25 µm.

![Figure 8. Laboratory prototype calibration and linear fit at the slit center. Eight spectral emission lines were taken into account.](image1)

![Figure 9. Smile (<1 pixel) of the spectral line of Argon corresponding to 912.3 nm. A parabolic fit is also shown.](image2)

5. Conclusions
The work presented in this paper allows building high quality and low cost Offner imaging spectrometers. A rapid and efficient method was used for the design, assembly and calibration of this type of spectrometers. A reliable alignment strategy has been developed which allows a complete alignment process in a few hours. Following this methodology, a laboratory prototype was built that shows high spectral and spatial resolutions and low distortions without use of specific aberrations corrected gratings nor non-spherical elements.

Acknowledgments
The authors hereby express their acknowledgment to the Xunta de Galicia for providing financial support under the contract 07MDS035166PR. Héctor González Núñez acknowledges support to the Xunta de Galicia by María Barbeito Program.
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