

Low-Distortion Imaging Spectrometer Designs Utilizing Convex Gratings

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Abstract

Several designs are described that are based on the Offner concentric spectrometer form, with the grating formed on the convex secondary mirror. It is shown that these designs permit the reduction of spectral and spatial distortion to a small (~1%) fraction of a pixel, while also providing a compact form with excellent optical correction. These designs can satisfy the needs and tight calibration requirements of imaging spectrometers for Earth remote sensing, over a broad spectral range from the ultraviolet to the thermal infrared. The practical realization of the designs owes much to the recent development of convex grating fabrication by electron-beam lithography.

1. Introduction

The requirement for very low distortion in pushbroom imaging spectrometers has been recently recognized. It has been shown that the spectral response function of a pixel must be known with great accuracy.¹ A small uncertainty in the location of the peak of this function can lead to significant error in the calculated pixel radiance. A maximum shift of less than 1% of the spectral response function (e.g. 0.1nm in 10nm halfwidth) has been identified as desirable in order to produce data that are free of significant spectral calibration errors.

Although elaborate calibration methods can conceivably reduce the effect of such errors, it is nevertheless desirable to start with a design that lessens the need for and dependence on such methods. The 1% maximum shift translates to a distortion value of $1/100^{\text{th}}$ of a pixel, a value that is well outside the range of familiar optical designs. The designer was thus requested to investigate novel spectrometer forms that are capable of such low distortion both in theory and in practice.

The spectrometer designs that were found capable of such performance were based on the Offner reflective relay.² Concentric spectrometer forms have been recognized for their potential for providing good optical correction and compact size.^{3,4} However, the requirement for submicron distortion has not been explicitly evaluated. In addition, lack of an appropriate technology for grating fabrication has made difficult the practical realization of these designs and has limited the interest in these spectrometer forms.

Progress in electron-beam lithography techniques has permitted the fabrication of high-performance convex gratings that are a perfect solution to the above problems. Specifically, such gratings can be produced with the required substrate convexity, while providing flexibility in the following grating parameters: variation of the blaze angle (or lack thereof) across the grating, control of the shape of the different blaze areas (if more than one area is desirable), control of the average diffracted phase difference between different blaze areas, control of the groove shape (beyond sawtooth or sinusoidal), and precise control of the grating pitch, including any desirable variation. All these properties impact the distortion and image quality characteristics of the spectrometer, so they are of importance to the optical designer.

In this paper it is shown that the Offner spectrometer design is an extremely flexible form that can satisfy the stringent and varied requirements of imaging spectroscopy, with only three spherical reflective surfaces and a compact form. The level of simplicity and performance that can be achieved should make this design form the preferred one for many imaging spectrometry applications. Some non-imaging applications are also briefly reviewed in the last part of the paper.

2. Types of Distortion

A pushbroom imaging spectrometer produces a dispersed image of a slit onto a detector array. We can think of the slit image as being parallel to a detector array column, while the spectrum is obtained along the rows. For the purposes of this discussion, we will assume that the array can be rotated with sufficient accuracy to match the orientation of the slit or spectrum.

The first distortion requirement is that the monochromatic image of the slit should remain straight and parallel to a column within a small fraction of a pixel, for any wavelength. A traditional way of relaxing this requirement is through the use of a curved input slit, but a straight slit is preferable in terms of ease of fabrication and alignment. Further, if the slit is curved one would then have to ensure that the curvature is independent of wavelength, which may be harder to achieve than no curvature at all. The second distortion requirement is that the spectrum of any point along the slit be straight and parallel to a row of the detector array. There is no way comparable to a curved slit that would ameliorate departure from this condition. These two types have been called spectral and spatial distortion. But the names are not intuitively obvious since both can apply equally to either type; hence they are avoided here. In their place, the term "smile" is used to represent the curvature of the monochromatic slit image and the term "keystone error" to represent the deviation from parallelism between the spectrum of a point and a row (that cannot be corrected by rotation of the array). The first term is hopefully obvious; the second term derives from the fact that the spectrum of the entire slit often (but not always) has the appearance of a keystone, the red slit image being longer than the blue for example.

It should be evident that lack of smile and keystone error will permit the easiest interpretation of the spectral information acquired from the spectrometer, and will also require the least amount of correction through elaborate calibration procedures.

3. Optical Characteristics of the basic Offner Spectrometer

The basic Offner spectrometer form is shown in figure 1. It comprises two reflective surfaces, one of which is used as primary and tertiary. The grating is on the convex second surface. In the original embodiment, the two mirrors are concentric. The slit is typically oriented perpendicular to the plane of the paper in figure 1(a), and parallel in figure 1(b). Ignoring for the moment the grating (or considering the 0th order), we have the following Gaussian properties. The magnification is -1, the stop is at the grating, and hence the entrance and exit pupils are at infinity. The primary aberrations of the two mirrors tend to cancel since the convex mirror has twice the power of the concave one, but the latter is used twice. Also, it may be seen that the system is symmetric about the stop. This normally means that coma and distortion will be absent.

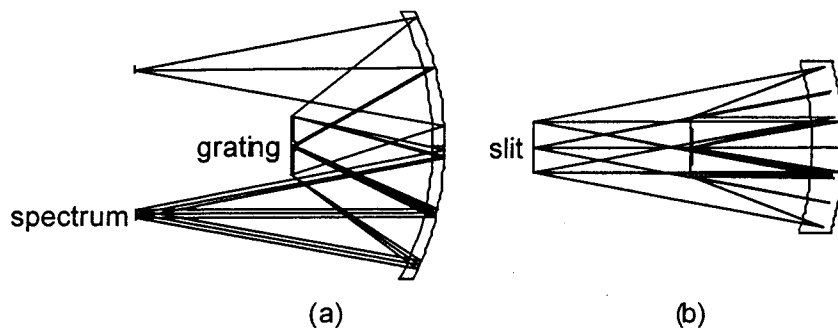


Figure 1. Basic Offner spectrometer, shown in two sections. The scale is approximately 0.5. In (a), the y-z section is shown. The slit is perpendicular to the paper. Three wavelengths are shown as coming to a different focus at the spectrum plane. In (b), the slit length can be seen (x-z section). The image of the slit is practically coincident with the object in this case.

Diffraction at the grating will destroy this symmetry, but it is clear that the Offner relay is a good starting point if one wishes to minimize distortion while maintaining good image quality. However, this break in symmetry means that it may be advantageous to use separate primary and tertiary mirrors and allow the spectrometer to depart from the ideal concentric form.

In order to proceed further, we need to assume some specifications typical of imaging spectrometry for Earth remote sensing. An imaging spectrometer may be required to cover the spectral range 400-2500nm with a spectral resolution of less than 10nm. It is also desirable to have a large number of spatial pixels, say 1000. The actual ground spot size and field angle will be determined by the focal length of the foreoptics, which are of no concern here. It should be clear that a single grating cannot cover such a wide spectral range with sufficient efficiency in a single order. Thus there are two possibilities: either use two (or more) spectrometer modules, or use a single spectrometer module in which the grating covers the shorter wavelengths in the second order.

4. Optical Performance Comparison between Two-Mirror and Three-Mirror Spectrometer Modules

The above specifications allow us to perform a comparative evaluation of various designs. We add as general design goals that both smile and keystone error should remain at a small fraction of a pixel, that the PSF ensquared energy within a pixel should be greater than ~80% for all fields and wavelengths, that the spectrometer should be as compact as possible, and that no vignetting should be permitted. This last requirement allows a comparison between the various forms on a less than arbitrary basis, since it places a limit on how close the slit can approach the optical axis.

A starting point for the design can be generated readily from the basic form of two concentric reflectors. One must then choose a suitable merit function. All calculations and optimizations reported here have been performed with ZEMAX. The merit function was constructed by selecting the chief rays from various parts of the field and for three wavelengths spanning the desired spectral range. The intersections of these rays with the image plane were then noted, and the differences in their x or y coordinates were set to zero. These differences represent components of the smile and the keystone error, so by minimizing them, those two errors are controlled. The remainder of the merit function was concerned with optimizing the spot size (or rms wavefront error) as usual. The relative importance of the distortion errors vs. spot size was controlled through the weighting factors assigned to the distortion terms. The condition of minimum distortion was often sufficient to ensure that the design did not stray from the unit magnification, telecentric condition, so insertion of the Gaussian properties in the merit function (or their control through solves) was rarely found necessary. Finally, it was found usually advantageous to use the +1 diffracted order of the grating (for which the angle of diffraction is less than the angle of reflection of the 0th order).

When correction for distortion is sought to such an extent, the difference between the centroids of the geometrical and diffraction spots is potentially of importance. However, theory shows that the two will coincide⁵ in general. Nevertheless, the practical limit to the distortion correction that can be achieved should be a matter of experimental investigation; a report on that is forthcoming.

The first two designs examined show a short-wave infrared (SWIR) spectrometer operating in the range 1000-2500nm. We assume an 18mm slit (1000x18 μ m) and 150 spectral pixels (pixel size 18 μ m square), and an f-number of 2.8. The design schematic is the same as in figure 1. This spectrometer was optimized by allowing both the mirror and the grating curvatures to vary, in addition to the mirror separation and the final image location. The Offner design is scalable, and generally improves with increasing size (while keeping the slit length constant) since the effective field is then reduced. Diffraction-limited performance is possible with a large enough size. However, the design aim is to maintain the most compact form possible, consistent with the ensquared energy and distortion specifications stated previously. The characteristics of the spectrometer shown in figure 1 are then compared against the spectrometer of fig. 2, in which the primary and tertiary are allowed to vary separately. Both were optimized with the same merit function. The comparison is shown in Table 1. The spectrometer size is taken as the total volume inclusive of slit and

image plane without folding, and is $\sim 12 \times 9 \times 7 \text{ cm}^3$ in both cases. Both spectrometers involve only spherical, nearly concentric mirrors, with no tilts. The ensquared energy (diffraction-based) and Strehl ratio refer to the worst case (field) for that wavelength. Similarly, the smile is the maximum obtained for any wavelength.

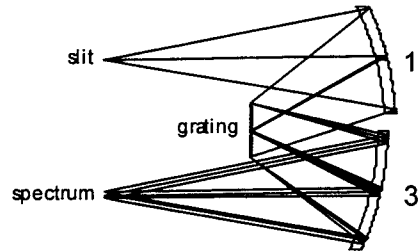


Figure 2. A three-mirror Offner spectrometer module, with similar specification as the one in Fig. 1 (y-z section).

Table 1
Performance comparison between two-mirror and three-mirror SWIR spectrometers

Version	Smile (fraction of pixel width)	Keystone (fraction of pixel width)	Ensquared energy @ 1 μm	Ensquared energy @ 2.5 μm	Strehl ratio @ 2.5 μm
Two-mirror	0.8%	1.1%	88%	67%	0.48
Three-mirror	0.7%	<0.1%	88%	78%	0.72

As Table 1 shows, both spectrometer forms have essentially zero smile and keystone error, but the two-mirror version suffers in terms of spot size at the longer wavelength. It would have been possible to trade some of the distortion correction for improved PSF, but the point is that the two-mirror version is harder to optimize simultaneously for distortion and PSF. Another way to compare the two designs is to allow the two-mirror version to grow until the PSF as well as the distortion are within specification, and then compare the size of the two versions. The necessary size increase is a non-negligible 50%, which shows that there is an advantage in splitting the primary and tertiary in this case. Whether or not that advantage is desirable, given the increased complexity of the three-mirror vs. the two-mirror version, will depend on whether the utmost performance is sought. It may be noted here that the requirement of maximum energy within a pixel does not arise from imaging considerations, but rather from spectroscopic/radiometric accuracy. If imaging alone was the issue, a considerably greater amount of energy could be allowed outside the pixel before the system MTF would drop too low at the Nyquist limit (as determined by the detector pixel size). This would make the two-mirror version the preferred one.

One of the great advantages of the Offner form is its compact size. If the pixel size is small enough and the required dispersion not too large, the spectrometer can be made very small. The next design example is a visible, near-infrared (VNIR) spectrometer, for which we assume a spectral resolution of 4nm, a pixel size of 10 μm square, a slit length of 1cm (1000 pixels), and an f-number of 4 (often adequate for this spectral region). The total volume of this design is $\sim 43 \times 30 \times 30 \text{ mm}^3$. Table 2 shows the comparison between a two-mirror and a three-mirror version as before. It can be seen that in this case the use of separate primary and tertiary provides no real gain.

Table 2
Performance comparison between two-mirror and three-mirror VNIR spectrometers

Version	Smile (fraction of pixel width)	Keystone (fraction of pixel width)	Ensquared energy @ 0.4 μ m	Ensquared energy @ 1 μ m	Strehl ratio
two-mirror	0.5%	<0.1%	87%	75%	N/A
three-mirror	0.6%	<0.1%	88%	79%	N/A

The size difference between the SWIR and the VNIR modules shown so far is due to the pixel size and the f-number. For example, if we allow a pixel of 27 μ m in the SWIR (a common size), and maintain the f-number at 4, then the spectrometer can be as compact as 10x6.5x5.2cm³, while maintaining over 80% of PSF energy within a pixel for all fields and wavelengths. The smile and keystone are well below the 1% pixel level tolerance. The slit in this case is 27mm long, so the lack of any distortion is a remarkable feature of this design. The relative size of the slit with respect to the spectrometer can be appreciated from figure 3.

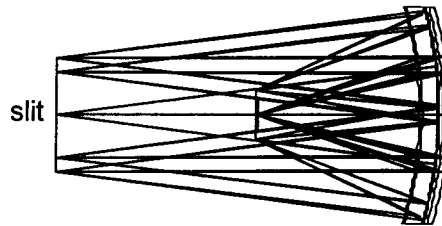


Figure 3. x-z section of a three-mirror compact Offner spectrometer with a long (27mm slit) and no distortion. The scale is approximately 0.75.

In comparing two-mirror vs. three-mirror versions, it should be appreciated that the added flexibility of the three-mirror version in terms of pupil matching with the foreoptics may be important on occasion.

4. A combined VNIR/SWIR spectrometer.

When a single foreoptic feeds both VNIR and SWIR spectrometers, the slit and pixel sizes must be the same for both if they are to cover the same field of view (FOV) with the same resolution. This reduces the flexibility in producing a miniature VNIR spectrometer otherwise made possible by the smaller pixel sizes available. In order to avoid a large increase in volume, it is sometimes possible to integrate both spectrometers into one, using a common grating and a dichroic (e.g. long-pass) filter as beamsplitter.

The example shown in figure 4 uses a coated fused silica plate that reflects the VNIR and transmits the SWIR band. The grating diffracts the SWIR in the first order, and the VNIR in the second order. Details of grating designs that can satisfy this broadband diffraction efficiency requirement are shown in ref. 6. This design has a 2cm long slit and operates at f/4, with a combined primary and tertiary. The spectral resolution is 10 nm/pixel in the SWIR and 5 nm/pixel in the VNIR. The design achieves negligible smile and keystone (<0.5%) for both focal planes simultaneously. In addition, the ensquared energy is greater than 78% at the longest wavelength and greater than 85% in all other cases, assuming a 27 μ m square pixel. This performance is achieved only by introducing a wedge angle in the beamsplitter plate (\sim 0.5 $^\circ$), and also by allowing a tilt of \sim 1.5 $^\circ$ in the SWIR focal plane.

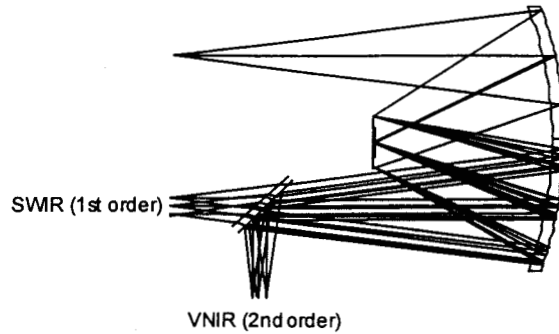


Figure 4. A combined VNIR/SWIR low-distortion spectrometer. The scale is approximately 0.75

5. A low f-number spectrometer for the thermal IR.

The thermal IR in the 8-12 μm region places new demands on reducing the f-number. As the spot and pixel sizes increase, the corresponding maximum number of pixels is reduced due to size limitations in IR array fabrication techniques. Thus it is important to maintain the lowest f-number possible. The design example shown in figure 5 (shown with a focal plane filter) is an $f/2.2$, with 60 micron pixels, and a 21.6 mm slit giving 360 spatial pixels. Spectrally, it has 64 pixels over the range 8-11.6 μm . The total volume (including object and image) is 13x14x8cm, which is still rather compact for this type of spectrometer. The energy within a pixel is 75% for the worst-case field and wavelength combination, and greater than 80% elsewhere. The smile is $\sim 1.3\%$ and the keystone error is practically zero. Once again, the spectrometer comprises only spherical surfaces, with no tilts or decenters.

One consideration for the thermal IR is the location of a cold stop. This design does not offer a convenient location for a cold stop because of the telecentric arrangement. A cold conical shield extending out from the photodetector can be used.

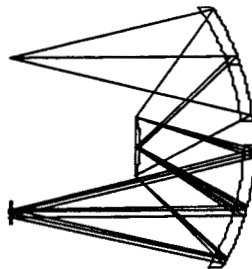


Figure 5. An $f/2.2$ low-distortion spectrometer for the 8-12 μm range. The scale is approximately 30%.

6. Non-imaging applications.

A long slit is not always required, as the spatial image may be acquired by scanning in two dimensions. Though the heading of this section implies a pinhole input, it is in fact possible to use a short slit of a few mm with any of these designs without observing appreciable performance degradation in terms of spot size. Thus these designs may be thought of as simply offering a reduced number of spatial pixels in return for extremely compact size, high spectral resolution or some such combination of features.

The example shown in figure 6 is a high-resolution design that gives 1 nm per pixel in the 0.92-1.32 μm range, and a 2 nm resolution in the 2.1-2.5 μm range, with a 6mm slit. The grating is used in two orders simultaneously. The two spectral bands may be separated with a dichroic beamsplitter (not shown). This design is optimized for spot size (>77% ensquared energy in 18 μm pixels) but not for smile or distortion, since these were not important for this application (not a pushbroom scanner). In order to achieve the high spectral resolution, the grating is used in near-Littrow mode. The resulting system is very compact, measuring only 7x3.5x3 cm^3 (larger if a beamsplitter and two focal planes are included). This spectrometer involves only one optical surface other than the grating. Both surfaces are spherical.

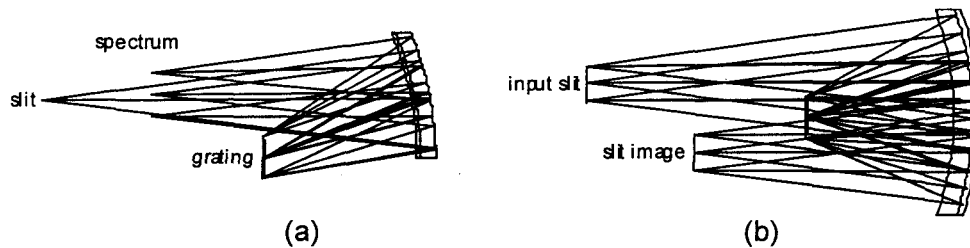


Figure 6. A high-resolution concentric spectrometer with the grating in near-Littrow mode (scale ~ 1).

7. Convex grating issues.

The ease and flexibility with which convex gratings can be manufactured using electron-beam lithography make these spectrometer forms desirable in practice. While it is possible to make the gratings using ruling or holographic techniques, the E-beam gratings have been shown to provide superior performance in terms of diffraction efficiency, wavefront quality, and scatter.⁶ In the designs presented here the grating blaze angle is typically less than a few degrees, while the substrate convexity is several times that amount. It is thus difficult to produce a blazed grating for high efficiency. Ruled gratings on curved substrates will generally suffer from variation of the blaze angle across the surface. Holographic gratings must be ion-etched in a continuously variable fashion across the grating in order to approximate the ideal blazed profile on a curved surface. The E-beam technique can produce gratings with great flexibility in the groove profile, as well as other grating characteristics. It is even possible to modify the grooves to produce an aberration-correcting grating. Although designs incorporating such gratings are not shown here, it has been found occasionally possible to improve the ensquared energy through this technique, while maintaining the low distortion for a long slit.

The designs presented up to this point have assumed a perfect grating. The optical design software cannot directly account for grating efficiency, but it is possible to do so indirectly. In the case of a multipanel grating, or a grating with a blaze angle variation, the efficiency may be predicted as a function of wavelength, and the resulting efficiency map across the grating can be modeled as pupil apodization. For a multipanel grating, the phase difference between panels must also be considered, and it may be the deciding factor in determining the shape of the PSF. In general, this phase difference is not known in advance as it depends on fabrication tolerances. However, one may make some inferences regarding the desirable grating characteristics from simple considerations.

If it were possible to satisfy the demands of the design with a single-panel ruled grating, the grating efficiency would then vary from the left to the right. So, for example, the left side might diffract more strongly the long wavelengths, while the right side might diffract the short wavelengths. At the long wavelength, the efficiency of the right side may be so low as to be negligible, and the same thing would hold for the left side and short wavelength. An appreciation of the resulting effect on the PSF can be had by simply considering each half of the pupil to diffract the corresponding wavelength. This has a measurable effect on the distortion characteristics.

An E-beam grating can be made with no variation in blaze angle, and hence uniform pupil transmittance. In practice, a broader spectral response than is possible with a single blaze has often been found desirable. This is accomplished by creating a two-panel E-beam grating, with each panel blazed at a different angle. The advantage of the E-beam technique is that there is no restriction regarding the shape of the panels. By making the panels concentric (a circle and annulus) there is generally negligible impact on the distortion characteristics as a result of apodization. In addition, the e-beam technique allows control of the average diffracted phase from each panel, which cannot be achieved with conventional techniques. This and other characteristics of the E-beam gratings are described in ref. 6.

8. Conclusions

Several imaging spectrometer designs have been presented that achieve excellent optical correction while simultaneously reducing the distortion errors to negligible levels. The Offner spectrometer form with a convex grating as the dispersing element is a versatile design that can satisfy various requirements of imaging spectrometers over a broad spectral band, from the ultraviolet to the thermal infrared. The spectrometer can be very compact, with the largest dimension being between four and ten times the length of the slit. These designs are made possible to realize in practice thanks to the advantages provided by E-beam lithography grating fabrication.

The spectrometer calibration requirements in terms of the pixel spectral response function characteristics led to the tight tolerances for distortion. However, the spectral response function of a pixel is affected not only by the location of the central maximum (which is a function of smile), but also by the bandwidth, which is controlled by the shape of the PSF along the spectral direction. It would be desirable to have no variation, which implies a fully isoplanatic system. Such a requirement is not possible to achieve, but fortunately, the effect of the pixel and slit width ameliorate the demands on the PSF variation. Although not shown here, designs with a variation of not greater than a few percent in the halfwidth of the spectral response function have been produced.

One may wonder whether such low distortion values of less than a tenth of a pixel are meaningful or achievable in practice. An experimental program is under way to develop the techniques needed for the spectrometer to approach its design performance. Though the experiment is not complete yet, at the time of writing it was possible to align the camera array so as to record a spectral line on a single column of the detector array for the entire length of the array (with 13.5 μm pixel width). This is a promising start. In any case, the simplicity of these designs with two or three spherical, nearly concentric surfaces gives the best possible chance of approximating the theoretical performance in practice.

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