CubeSat Format 3-Mirror Spectrometer Designed with Freeform Surfaces

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Abstract: A design study about a 3-mirror freeform spectrometer that fits in a 1U CubeSat format. Performances are compared between the freeform and off-axis asphere designs.

OCIS codes: (080.4035) Mirror system design; (080.4228) Nonspherical mirror surfaces; (300.6190) Spectrometers.

1. Introduction

CubeSats are a type of miniaturized satellites that consist of 10×10×10 cm cubic units (1U), which is established as a standard by Jordi Puig-Suari and Robert Twiggs in 1999 to push low-cost educational and industrial space experimentation [1]. In recent years the CubeSat format has gained popularity for research and industrial purposes including Earth imaging, communication and technology demonstration. High performing optical systems such as spectrometers and imagers that can be contained in CubeSat format are also desired in many space missions.

In this paper, a design study is conducted for a 3-mirror spectrometer based on the reflective triplet design form that is fully contained in 1U space. As shown in Fig. 1, the spectrometer consists of three mirrors and a plane grating serving as the aperture stop. Light from a slit enters the system and travels through the three mirrors to the grating where it is dispersed and reflected. The light then travels back through the system in reverse to the detector near the slit which results in a 2D image (or spectrum). To show the freeform advantage, we compared two designs of this spectrometer - one designed with freeform surfaces and the other with off-axis aspheres.

2. Specifications

Table 1 summarizes the specifications, which both the freeform and off-axis asphere designs satisfy. The specifications were determined based on the general need for the spectral analysis for Earth imaging and the industrial standards on CubeSat and detector format. For the study purpose, the 1U volume constraint applies only to the optics without considering space occupied by additional mechanical and electronic components. The slit width is also not specified because its determination depends on specific applications.

Table 1. Specification table

Parameter	Specification
Waveband [um]	0.4 – 1.7
F-number	F/3.0
Detector format [mm]	12.5×10
Slit length [mm]	10
Size [cm]	< 10×10×10

3. Design Process Summary

The off-axis asphere design started from a reflective triplet telescope design (CODE V sample lens threemrc.len). The starting point was modified into a spectrometer with the aperture stop moved from the secondary mirror to the plane grating. Then the system was re-optimized with volume and obscuration constraints.

The freeform design started with an estimated layout with spherical surfaces. The freeform surfaces were described with Zernike polynomials centered at the centroid of all the light incident on the surfaces. Since the base radius of curvature and the conic coefficient were also used in describing the freeform surfaces, additional constraints are added to avoid degeneracy [2].

The realized spectral resolution is sensitive to the amount of keystone and smile distortion in the image. To investigate how distortion constraints affect image quality during optimization, both off-axis asphere and freeform designs were optimized with and without distortion constraints separately and the performance results are listed in Table 2. Layouts of the final designs are shown in Fig. 1.

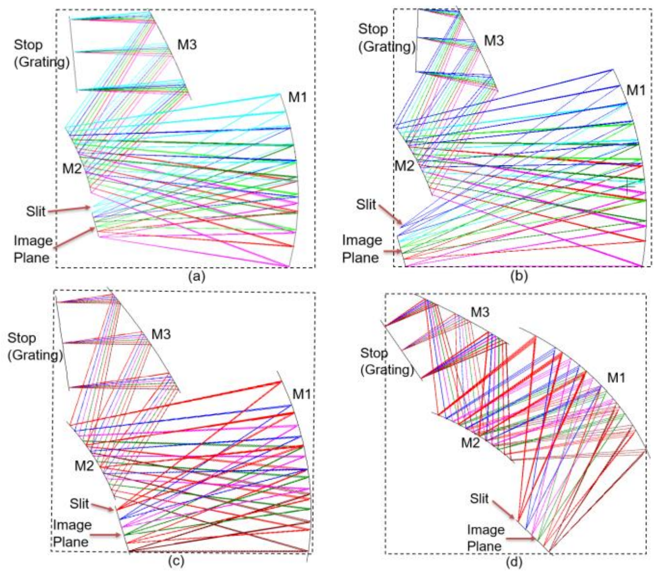

Fig. 1. Layout of designs for (a) off-axis asphere design without distortion constraints, (b) off-axis asphere design with distortion constraints, (c) freeform design without distortion constraints and (d) freeform design with distortion constraints. The dashed square represents 10×10 cm box.

4. Performance Comparison

Table 2 summarizes the performance comparison between off-axis asphere and freeform designs. Let us note that the distortion of the system is reported with spectral smile and keystone [3].

Table 2. Performance comparison between asphere and freeform designs

Design	Distortion Constraints?	Smile (µm)	Keystone (µm)	Average RMS Spot Size (µm)	Maximum RMS Spot Size (µm)
Asphere	No	< 14	< 77	3.00	5.70
Asphere	Yes	< 5	< 5	9.20	13.60
Freeform	No	< 110	< 76	0.76	1.28
Freeform	Yes	< 5	< 5	2.08	3.12

From Table 2, the distortion constraints do have a significant impact on image quality performance. By constraining the smile and keystone distortion to be less than 5 µm in both the off-axis asphere and freeform designs, the RMS spot size increased by a factor of about 2-3 in terms of average and maximum value across the field. However, with more degrees of freedom, the freeform design was able to keep the performance diffraction limited at most of the wavelengths while controlling the smile and keystone distortion under 5 µm. In this design form, the freeform designs have about 4x better RMS spot size than the corresponding off-axis asphere designs.

5. Conclusion

A design study was conducted for a 3-mirror spectrometer in the reflective triplet form and a performance comparison was reported between freeform and off-axis asphere designs. Under the same specifications (design form, volume and F-number) and distortion constraints, results show that freeform designs show a 4x smaller RMS spot size compared with off-axis asphere designs.

6. Acknowledgement

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7. References

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