

INTRODUCTION

This project aims to investigate the integration of freeform optics (FFO) within the CubeSat (CS) format. The objective is to develop a multispectral imager for Earth Observation (EO). The camera will acquire images using the pushbroom technique, and a Linear Variable Filter (LVF) will be placed in front of a 2D detector to enable multispectral imaging. A two mirror off-axis Schwarzschild configuration, both with and without FFO, will be presented.

CUBE SATellites

- Nanosatellites
- Base unit "U" of dimension 1 dm³ and weight 1 - 2 kg (see Figure 1)

Advantages over traditional satellites:

- Cost effectiveness
- Rapid construction timelines
- Deploy multiple CS in series
- Lightweight design
- Act as secondary payloads: more accessibility to space
- Deploy a satellite constellation: achieve complex objectives [1 - 3]

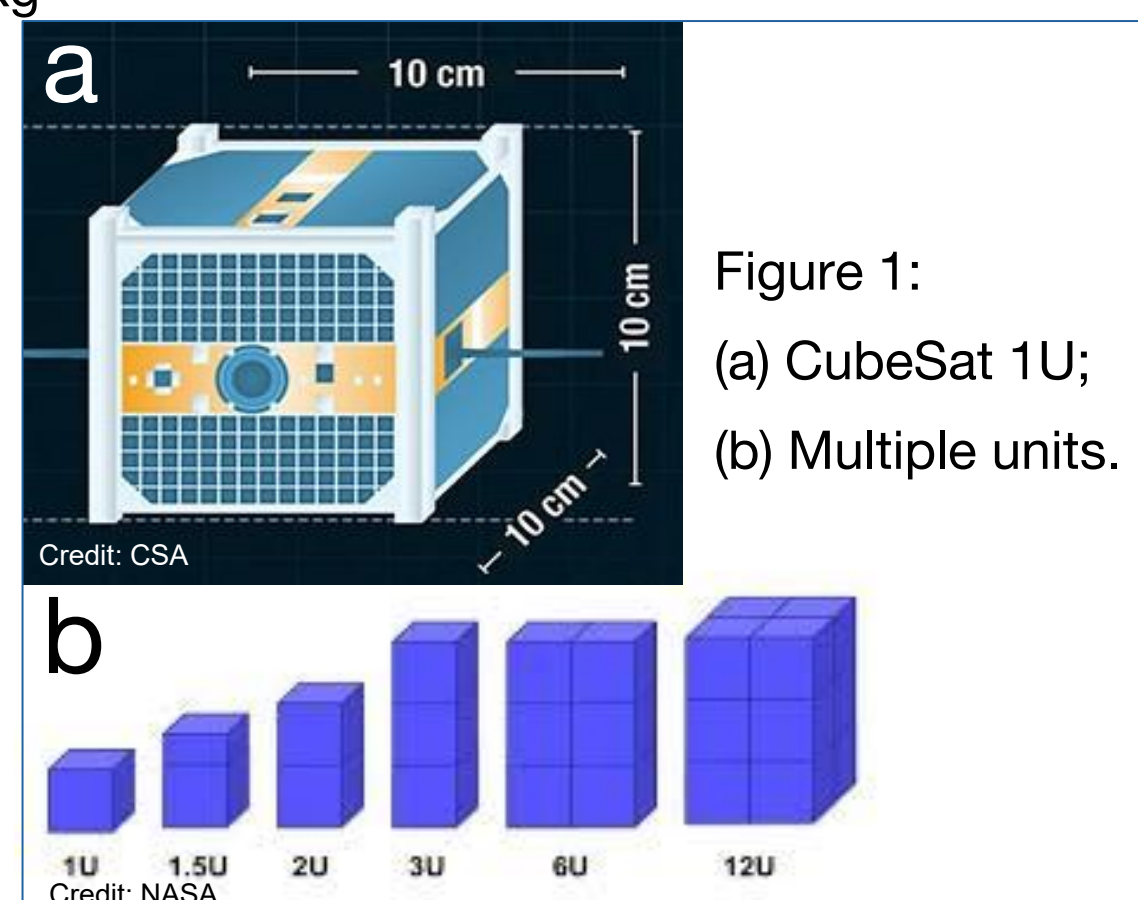


Figure 1:
 (a) CubeSat 1U;
 (b) Multiple units.

FREEFORM OPTICS

Optical surfaces that lacks translational or rotational symmetry within or beyond the optical part [4 - 6].

Advantages of freeform over traditional optics (see Figure 2)

- Reduce aberrations over a wider FoV keeping the same volume:
 Improve optical performance
- Reduce the number of optical components:
 Multiple functions into a single element
- Miniaturize the optical system, reduce volume and weight keeping the same performance:
 More compact system

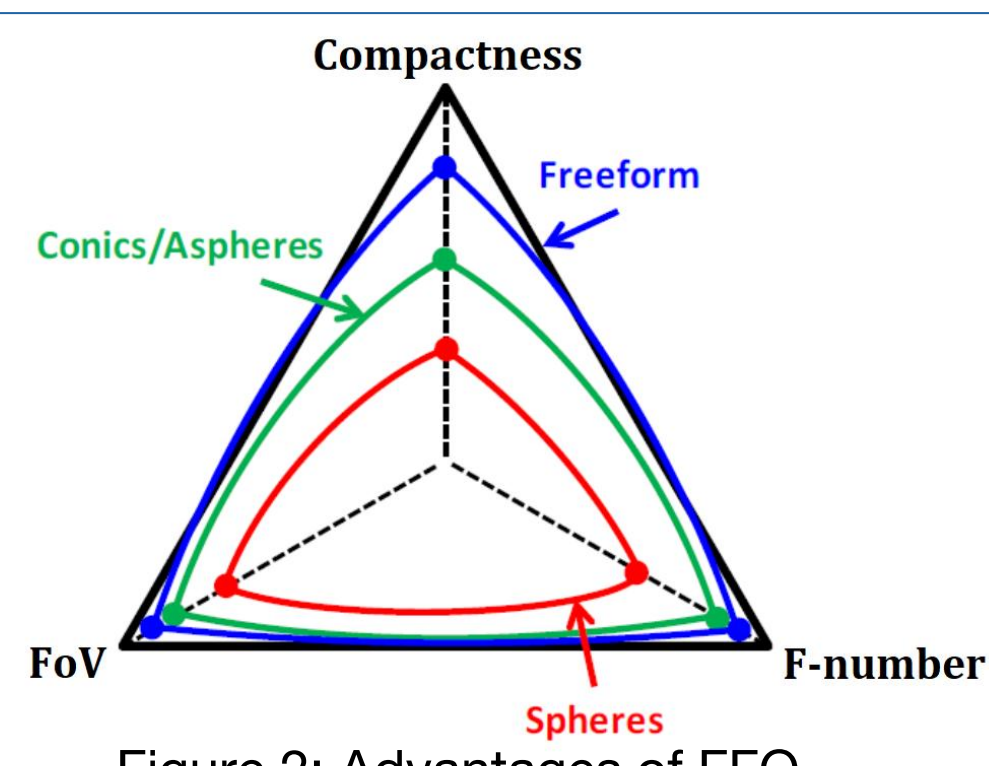


Figure 2: Advantages of FFO.

Freeform optics can be described by analytical functions: Zernike polynomials [7].

$$\text{Sag departure} \rightarrow z(\rho, \theta) = z_{\text{basic shape}}(\rho) + z_{\text{complex shape}}(\rho, \theta) \quad (\text{Zernike})$$

SYSTEM OVERVIEW

The instrument specifications and the results of the radiometric model [8] to determine the Signal to Noise Ratio (SNR) are presented in Table 1 and Figure 3. The concept of LVF for multispectral imaging is shown in Figure 4.

Table 1: Instrument specifications.

Parameter	Value
Spectral range	400 nm – 900 nm
CS dimension	12U Optical part = 8U
GSD	41.3 m
Orbital height	450 km
Focal length	60 mm
Aperture size	36 mm
F#	1.67
Detector pixel size	5.5 μm
Field of View	12° along the spectral direction 4° along the spatial direction
MTF	> 50% @ 50 lp/mm

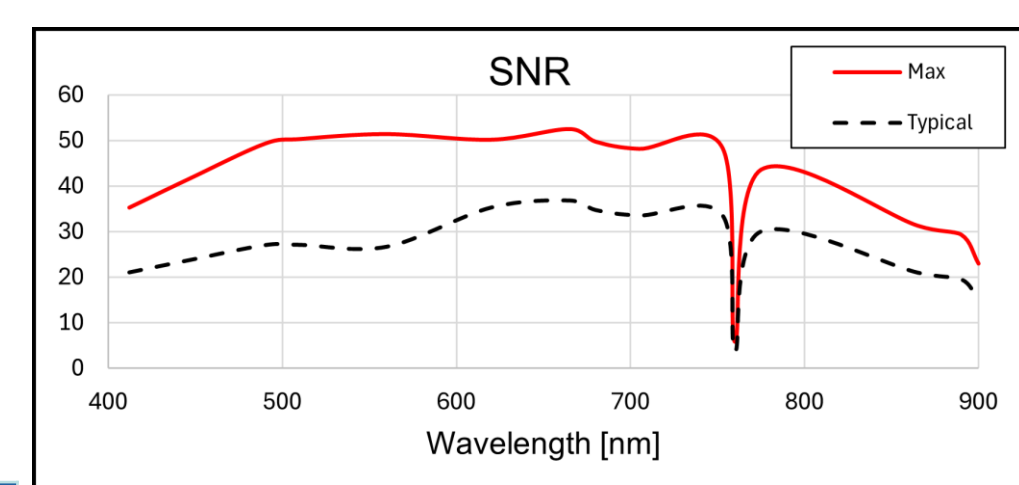


Figure 3: Signal to Noise Ratio.

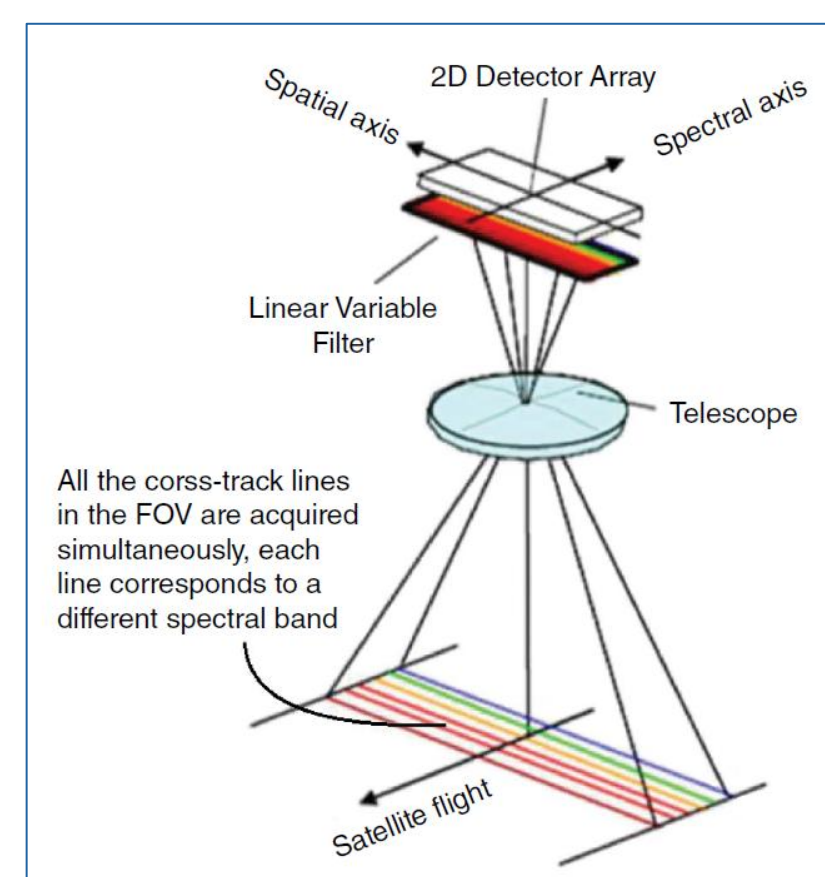


Figure 4: Illustration concept of LVF placed in front of the 2D detector array [9].

TWO MIRROR CONFIGURATION

Table 2 reports the characteristics of the off-axis Schwarzschild optical design [10] developed with ANSYS Zemax OpticsStudio to be analysed with FFO.

- M1: convex mirror, defined as the aperture stop.
- M2: concave mirror.
- Physical dimensions: 160 × 175 × 108 mm³ (fit within an 8U CS).

Figure 5 presents the final optimized optical design.

Table 2: Design characteristics of the off-axis Schwarzschild configuration to be analysed with FFO. The Thickness refers to the distance between two consecutive surfaces: in this case to the distance between M1 and M2 (-120 mm), and M2 and the Image plane (+144.85 mm).

	M1 (STOP)	M2
Radius of Curvature [mm]	+ 169.71	+ 169.71
Thickness [mm]	- 120	+ 144.85
Conic Constant	+ 5.83	+ 0.172
Aperture Diameter [mm]	36	106

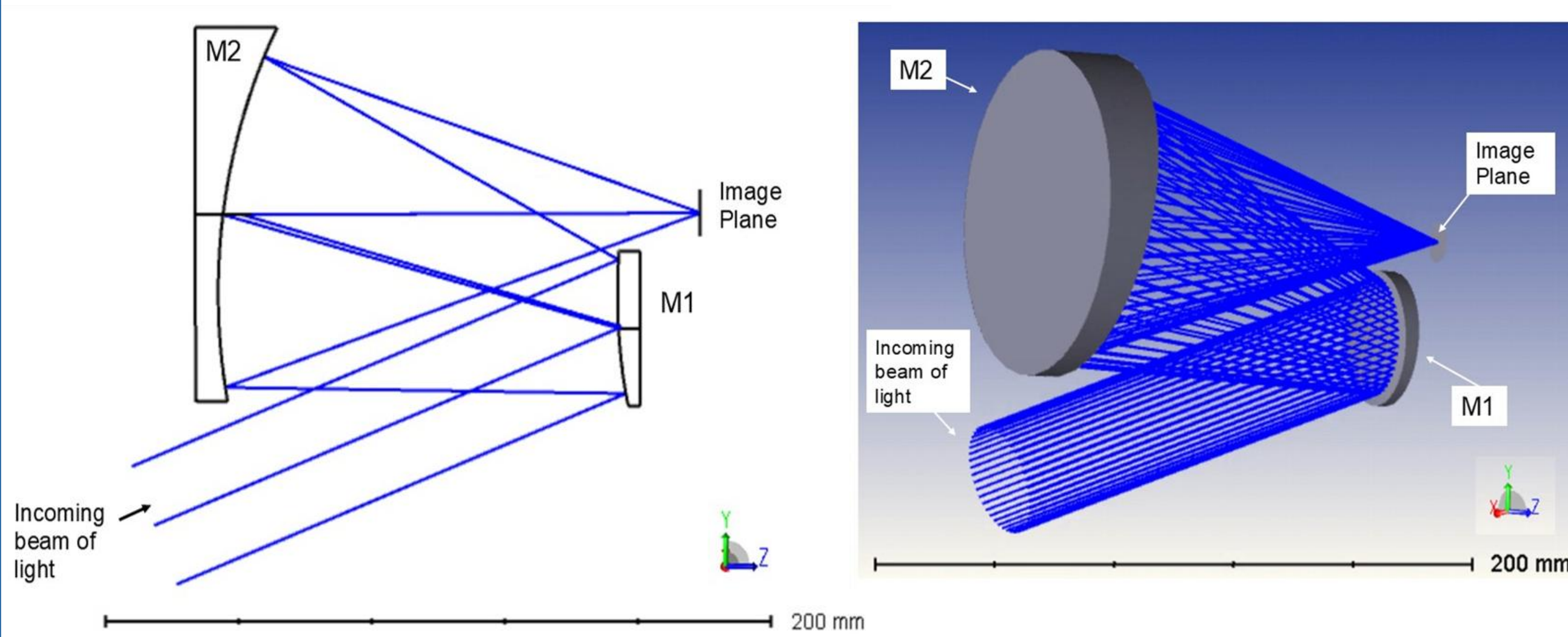


Figure 5: off-axis Schwarzschild optical design to be analysed with and without FFO. (a) 2D layout, (b) 3D layout.

TWO MIRROR CONFIGURATION: RESULTS

Figure 6 shows the Spot diagrams (a), Modulation Transfer Functions (MTF) (b), and Ensquared energy (c) without FFO (left panel) and with FFO (right panel). FFO were applied to both M1 and M2 to increase the number of degrees of freedom during the optimization process and the Zernike polynomials up to order 17 are used.

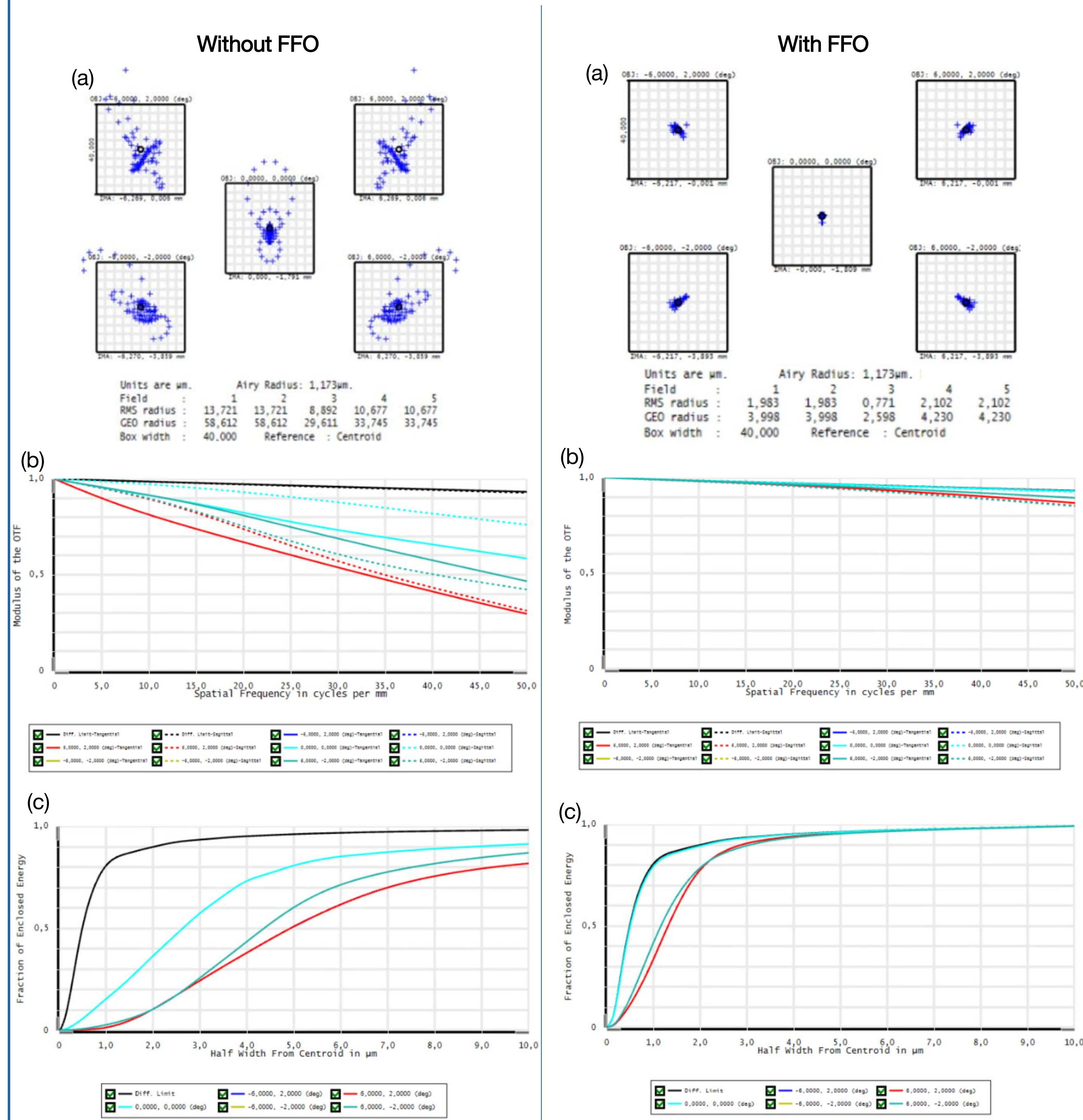


Figure 6: off-axis Schwarzschild configuration without FFO (left panel) and with FFO (right panel). (a) Spot diagrams at the image surface. The circle corresponds to the Airy disk at λ = 600 nm. The size of the black square box is 40 μm. (b) Polychromatic MTF up to 50 lp/mm. (c) Ensquared energy up to 10 μm from centroid. For both MTF and ensquared energy the legend items refer to the field positions.

- Spot diagram: RMS spot radius without FFO = 13.7 μm, RMS spot radius with FFO = 2.1 μm. The system is pixel limited (pixel size = 5.5 μm) with FFO.
- MTF: lower than 50% @ 50 lp/mm without FFO while higher than 50% @ 50 lp/mm with FFO.
- Ensquared energy: at 10 μm from centroid is >80% without FFO while >95% with FFO.

CONCLUSIONS

A comparative analysis between the classic off-axis Schwarzschild optical design and the FFO system was carried out. In the classic system, the design was far from being pixel limited, while in the FFO case, the system was pixel limited, clearly demonstrating that FFO can significantly improve the optical performance of the imaging system.

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