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UNIVERSITÀ DEGLI STUDI DI PADOVA

Freeform optics for space instruments

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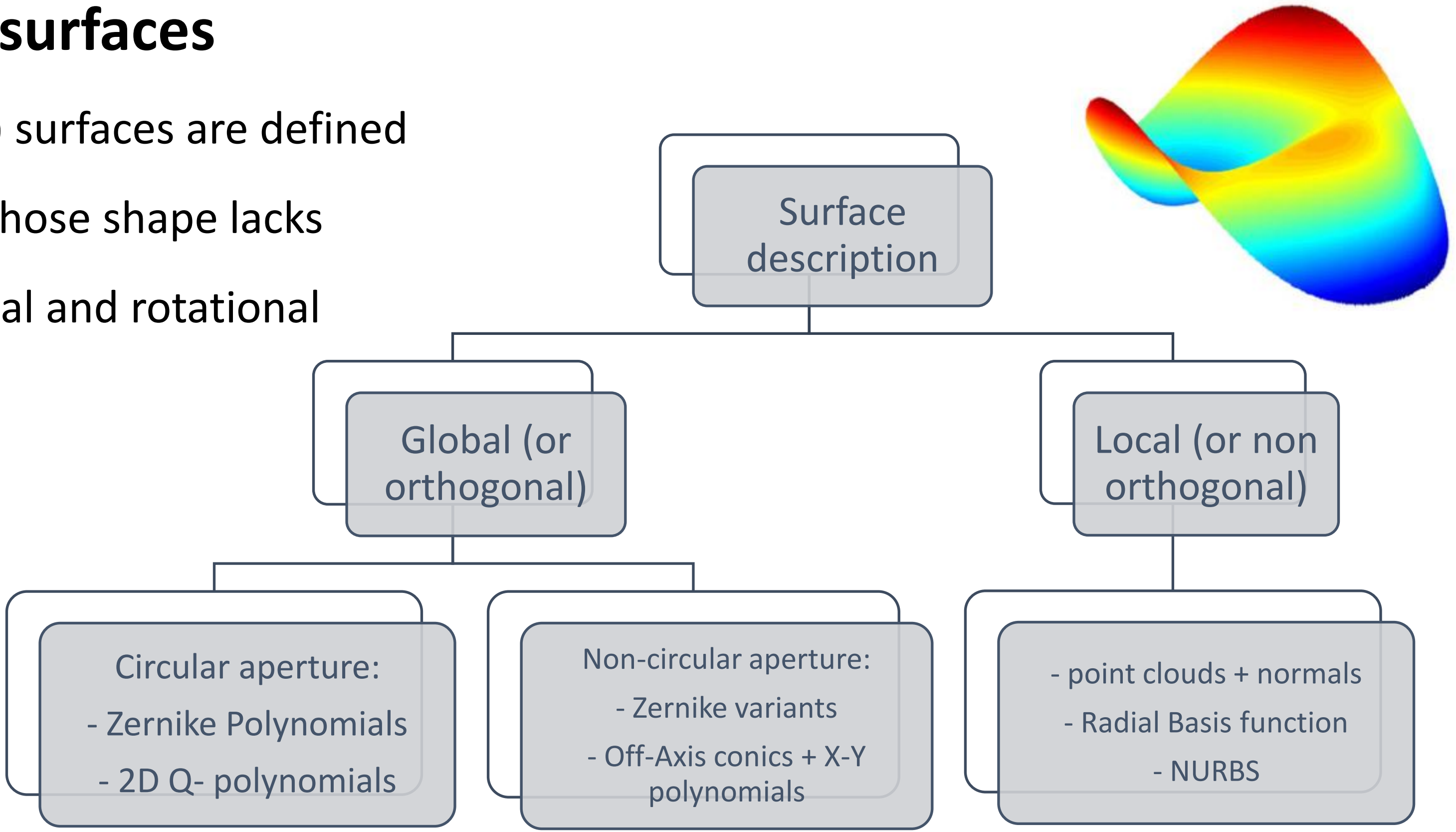
Co-Supervisor : Prof. Giampiero Naletto - Dott. Gabriele Cremonese

Admission to the second year - 13/09/2023

- Introduction
- Aberration behaviour for system with FF surfaces
- PRISMA SG spectrometer
- A case study: Freeform grating
- Future work

Freeform surfaces

Freeform (FF) surfaces are defined as surfaces whose shape lacks of translational and rotational simmetry.



Optical space Instruments typical requirements

Volume: Minimize the total amount of optical elements to maintain in an easier way the optical alignment.

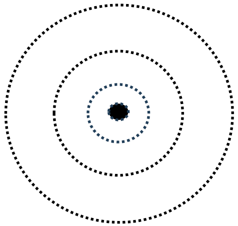
Optical quality: Correct optical aberrations to obtain clear and sharp images.

Manufacturing: Ensure the use of top-grade materials and manufacturing techniques for precision lenses and mirrors.

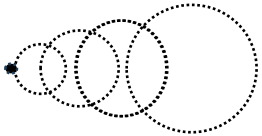
Designing optical space instruments demands a careful balance of precision engineering, environmental considerations, and advanced technology. Meeting these requirements is essential for the success of space exploration missions.

Optical Aberrations

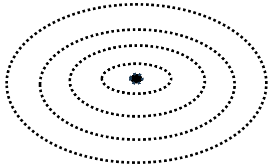
- Spherical aberration



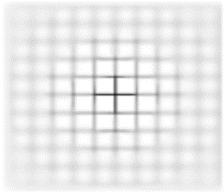
- Coma



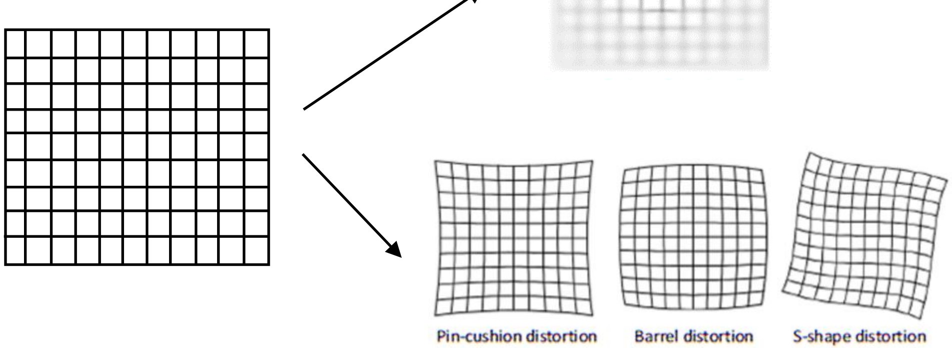
- Astigmatism



- Curvature of field

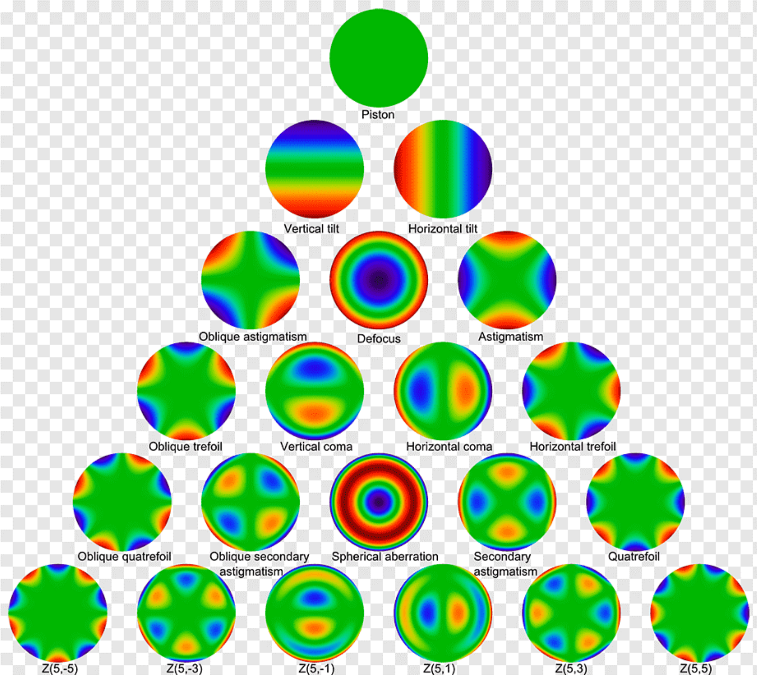


- Distortion



Aberration behaviour for system with FF surfaces

Zernike standard polynomials



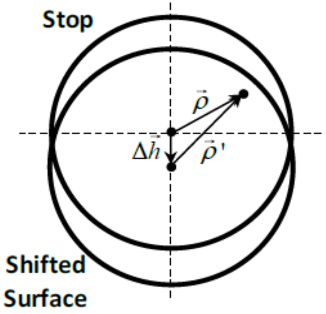
Zernike polynomial set through 6th order in wavefront expansion.

Z1 piston,
Z2/3 tilt,
Z4 defocus,
Z5/6 astigmatism,
Z7/8 coma,
Z9/10 elliptical coma or trefoil,
Z11 spherical aberration,
Z12/13 secondary astigmatism,
Z14/15 quadrefoil,
Z16 secondary spherical aberration

Aberration for system with freeform

A key point is that freeform optics have different impact in terms of aberrations contribution depending on their position in the system [1]:

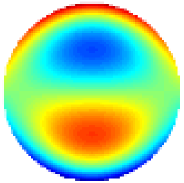
- If the FF is applied on a surface located at the stop, the net aberration is field constant, meaning that we have just the applied aberration.
- If the FF is applied on a surface away from the stop, the aberration becomes field dependent, and new correlated aberrations contributions appear.

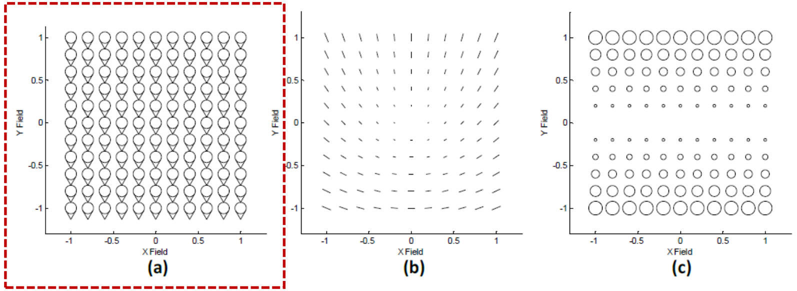


Aberration behaviour for system with FF surfaces

Field dependent aberration

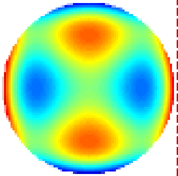
Adding **a coma shape (Z8)** away from the stop

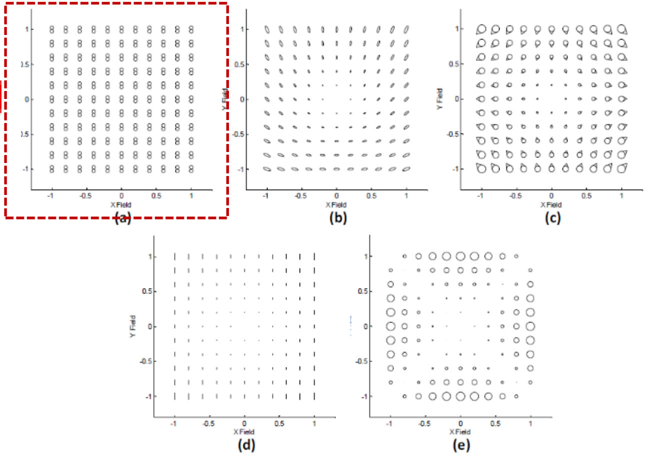




adds three types of aberration: Z4, Z5/6, Z7/8. [2]

Adding **a secondary astigmatism aberration shape (Z12)** away from the stop

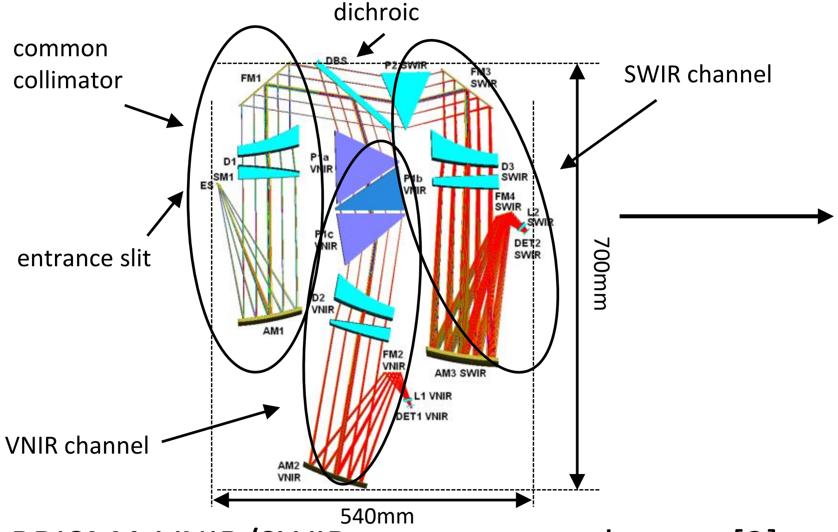




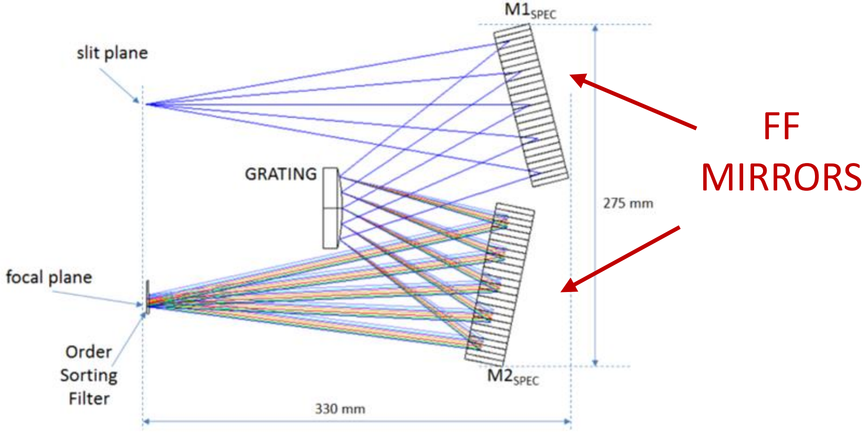
adds five types of aberration: Z4, Z5/6, Z7/8, Z10/11, Z12/13.[2]

PRISMA SG spectrometer

The layout of the instrument has been realized at Leonardo S.p.A. and it is based on the Offner-Chrisp spectrometer with an off-axis configuration. Its spatial resolution is of 10 m/pixel, over a field of view of 30 km. (x3 better than PRISMA spectrometer)



PRISMA VNIR/SWIR spectrometer layout. [3]



PRISMA SG spectrometer layout.

Designing PRISMA SG spectrometer…

- Different kinds of polynomials (Zernike, Chebyshev, XY) were studied to understand which should be the best compromise in terms of computational weight and performance.
- Freeform mirrors enables to increase the FOV maintaining a good distortions correction thanks to the great flexibility offered by the increased number of degrees of freedom.
- The spectrometer provides a good correction for smile and keystone distortions keeping a good optical quality over the whole FOV and spectral range.

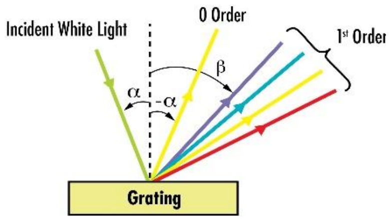
Next step of the design:

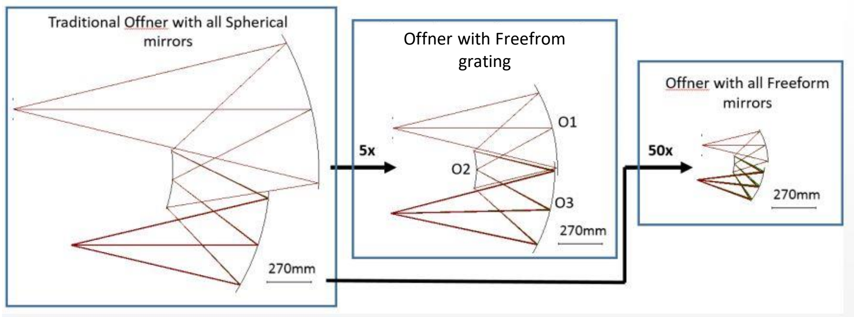
- Manufacturing and Alignment study

Freeform grating

From literature introducing FF grating allows to:

- Reduce of about a factor of x5 in volume.
- Correct aberrations and achieve a high resolution[6].
- Decrease the total number of optical elements.





Freeform grating

Case Study:

The aim of the activity is to understand the potential in terms of Field of View (FOV) by introducing a freeform grating in an F#3 Offner Spectrometer starting from the following requirements:

Parameter	Requirement
Spectral range	400-2500 nm
Smile	< 5µm
Keystone	< 3µm
MTF@14 cycles/mm	> 0.7
Grating dispersion	3.1 nm/mm

Design steps and maximun FOV achieved:

Layout with standard optics

- FOVmax = 51mm

Layout with conic grating

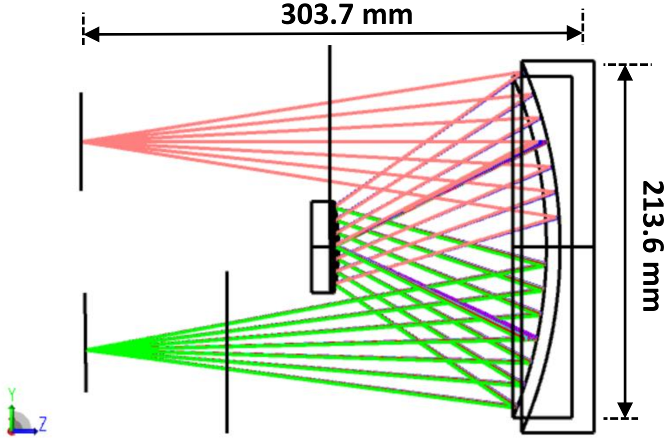
- FOVmax = 54mm

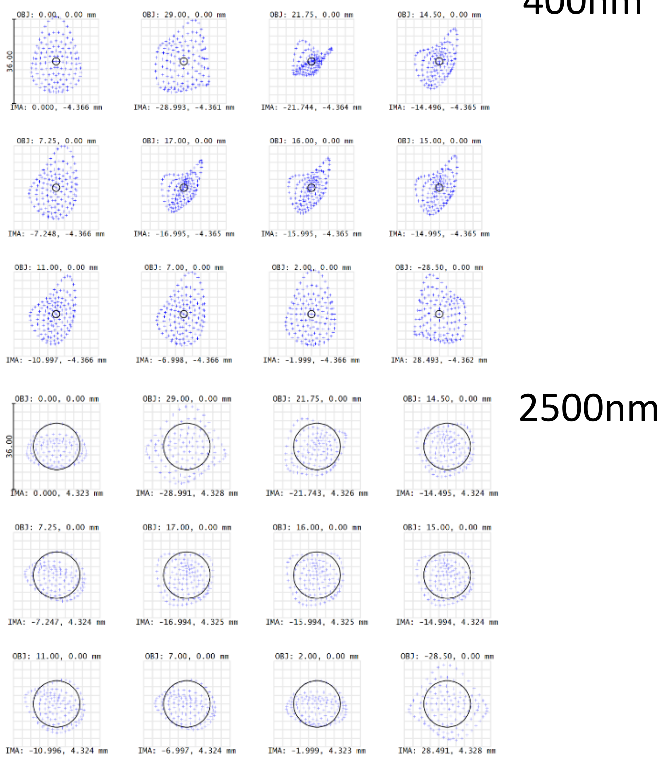
Layout with freeform grating

- FOVmax = 58mm

FoV of 58 mm with Freeform grating

Final parameters	
Keystone	1.326 µm
Smile	4.513 µm
MTF	> 0.700
n. coefficients	16





Future work

- Discover which are the limits of this technology and how much the performance can be increased thanks to freeform optics.
- Implement an algorithm to automatically move from one polynomial base to another for the freeform description.
- Study of the Breadboard of PRISMA SG spectrometer.
- Introduction of freeform surfaces to CubeSat's optical instrument aiming to reduce the dimension.

Progress of the work

GANTT CHART

PHD STUDENT	Chiara Doria	DATE	13/09/2023
PHD THESIS	Freeform optics for space instruments	ADMISSION TO	Second year

FIRST YEAR				SECOND YEAR				THIRD YEAR			
T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S

WBS NUMBER	TASK TITLE	% OF TASK COMPLETE
1	Bibliography research and preliminary mathematical design of freeforms optics	
1.1	State of art and theory of freeform optics	90%
1.1.1	Freeform applied to spectrometers	80%
1.1.2	Software simulations for raytracing	80%
1.2	Methodologies for the mathematical description of freeform optics	85%
1.2.1	Primary simulations of the design and performance	90%
2	Manufacturing of freeform mirroors for PRISMA second generation application	
2.1	Manufacturing study	30%
2.1.1	Mid-spatial frequency analysis	0%
2.1.2	Parametrizing in the optimal way the machine/tools	0%
3	Analysis of the performance of the mirror on the prototype of PRISMA	
3.1	Achieving of the best optical layout configuration	0%
3.2	Analysis of the effective performance of the mirrors on PRISMA	0%
4	Design of an optical layout for freeform application to miniaturize the satellite	
4.1	Deepening on the main applications of freeform optics on small satellite	0%
4.1.1	Deepening on the main structural advantages introduced by freeform optics	0%
4.2	Optical layout configuration for small satellite	0%

References

[1] K. Fuerschbach, J. P. Rolland, and K. P. Thompson, "Theory of aberration fields for general optical systems with freeform surfaces," Optics Express **22**, 26585-26606 , 2014.

[2] A. Bauer, E. Schiesser, J.Rolland, “Starting geometry creation and design method for freeform optics”. Nature Communications. 9. 10.1038/s41467-018-04186-9, 2018.

[3] Meini, M., Battazza, F., Formaro, R., and Bini, A., “Progress in the hyperspectral payload for PRISMA programme”, in Sensors, Systems, and Next-Generation Satellites XVII, 2013.

[4] B. Borguet, V. Moreau, A. Z. Marchi, M. Miranda, and A. Cotel, "CHIMA: Design and Performances of a Freeform Grating High Spectral Resolution Spectro-Imager," in Optical Design and Fabrication 2019 (Freeform, OFT), OSA Technical Digest (Optica Publishing Group, 2019), paper FM4B.2.

[5] A. Calcines, C. Bourgenot, R. Sharples, "Design of freeform diffraction gratings: performance, limitations and potential applications," Proc. SPIE 10706, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III, 107064Z, 2018.

[6] B. Zhang, Y. Tan, Guofan Jin, J. Zhu, "Imaging spectrometer with single component of freeform concave grating," Opt. Lett. 46, 3412-3415 (2021)

Thanks for the attention

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