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Freeform Offner spectrometer for space applications

Doria Chiara[1] *, Guerri Irene[2], Pekala Grzegorz[2], Cremonese Gabriele[3],
Naletto Giampiero[4,1], Taiti Alessio[2]

[1]Center of Studies and Activities for Space “Giuseppe Colombo” (CISAS), University of Padova,
via Venezia 15, 35131 Padova, Italy

[2]Leonardo S.p.A., via delle Officine Galileo 1, 50013 Campi Bisenzio (FI), Italy

[3]INAF- Astronomical Observatory of Padova, Vicolo dell’Osservatorio 5, 35122, Padova, Italy

[4]Department of Physics and Astronomy, University of Padova, Via Marzolo 8, 35131, Padova,
Italy

*chiara.doria.1@phd.unipd.it

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Abstract. The performance in terms of image quality and spatial resolution plays a key role for imaging space instruments. Modern advancement in manufacturing and testing introduced freeform optics to the scene. Thanks to a higher number of degrees of freedoms with respect to the classical optical surfaces, freeform technology is a great opportunity to improve the instrument performance. Here a freeform Offner spectrometer is presented: it has been studied for the PRISMA second generation (SG) instrument, which is dedicated to space application, and it is now at the design phase A at Leonardo S.p.A.

Introduction

In the last few years, freeform optics started to be highly used for imaging and non-imaging systems thanks to the advancement in design, fabrication, and testing fields. Even if requiring an expert knowledge in cross- disciplinary fields, freeform optics can give a huge improvement in terms of performance and instrument compactness. In this first part of the study the focus will be the improvement of the spectrometer performance thanks to the use of freeform optics. Higher compactness design adopting freeform optics will be analyzed in future works, specifically for CubeSat applications.

Background

The geometry of a freeform optical surface is characterized by an absence of an axis of rotational symmetry, thus allowing many more degrees of freedom with respect to standard (also aspherical) optics. Different studies show that there are significant advantages in using those kinds of surfaces in the optic fields, both in terms of optical performance and instrument compactness. These are two major points for space instrumentation, making their application very promising for the next generation of space optical systems.

For what concerns the fabrication of freeform optics, we can presently use numerically controlled machines for grinding, polishing, and diamond turning. The challenge in these techniques includes building knowledge of how materials behave and defining suitable procedures for the surface shaping process. Some exciting developments are the recent advances in additive manufacturing that enable the 3D printing of freeform optics substrates.

Despite all those difficulties to face, freeform optics have already been applied on many different areas such as optical transformation (e.g., quantum cryptography, art forms), lighting and illumination (e.g., luminance, architecture lighting, automotive), manufacturing (e.g., EUV lithography, laser materials processing, machine vision and inspection), mobile displays (e.g., near-eye, head worn handhelds, smart glasses), remote sensing (e.g., down-looking satellite, ubiquitous data collection, astronomical instrumentation, CubeSat), infrared and military instruments (e.g., UAVs and drones, conformal optics, and intelligence surveillance and reconnaissance systems) [4].

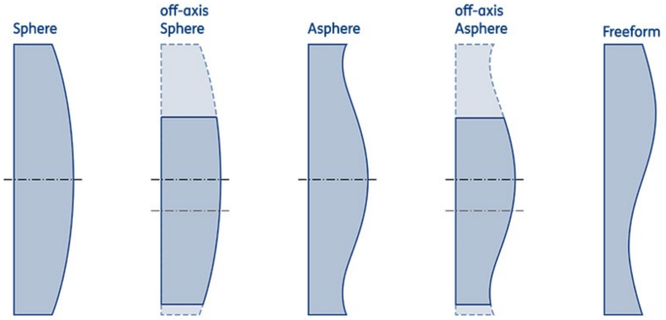


Fig. 1 Evolution of optical surfaces.

In order to introduce freeform optics in space instruments, one of the main issues is to find the best way of mathematically describe these surfaces: not only for designing and optimizing the optical surface by suitable ray-tracing codes, but also to have the correct input to the machines/tools with which these optics will be manufactured and tested.

There are many methodologies for the mathematical description of freeform surfaces, either local, also called non-orthogonal polynomials (XY polynomials, spline surfaces, radial basis function) or global, also called orthogonal polynomials (Zernike, Fringe Zernike, Q-type, Chebyshev) [1][2]. At this kind of analytical functions, we can add many new representation techniques, those employed to obtain a surface from discrete data points fitting, and the so-called hybrid or combined methods (usually applied when the surface presents big slopes).

For example, when using a Zernike polynomial, from the literature we know that the normalized expansion can be used to describe aberrations and the coefficient values of each mode represent the root mean square (RMS) wavefront error attributable to that mode [3]. The main coefficient order is described in Fig. 2.

A key point for the freeform description and analysis is the study of how the different terms of the polynomials affect aberrations, distortions and the main constraints of an optical design.
In addition, it is important to understand which the best design is to develop systems with great performance but not so much sensitive to manufacturing, mounting and stability tolerances.

From the many design methods presented in literature, here two methods are under study, both working on the minimization of the freeform system sensibility to a perturbation of the freeform system during the design phase.
The first one analyses the variation of the optical path difference due to a tilt perturbation: after the definition of a suitable function called error sensitivity function (ESF), it uses the Non-dominated Sorting Genetic Algorithm (NSGA-II) to minimize the ESF function and obtain a set of instrument design solutions. Then the ESF is exploited again to find the best polynomial description for the freeform surfaces [6].
The second method has been proposed to find the optimal design employing freeform surfaces less sensitive not only to tilt errors but to any perturbation applied to all optical elements [7].

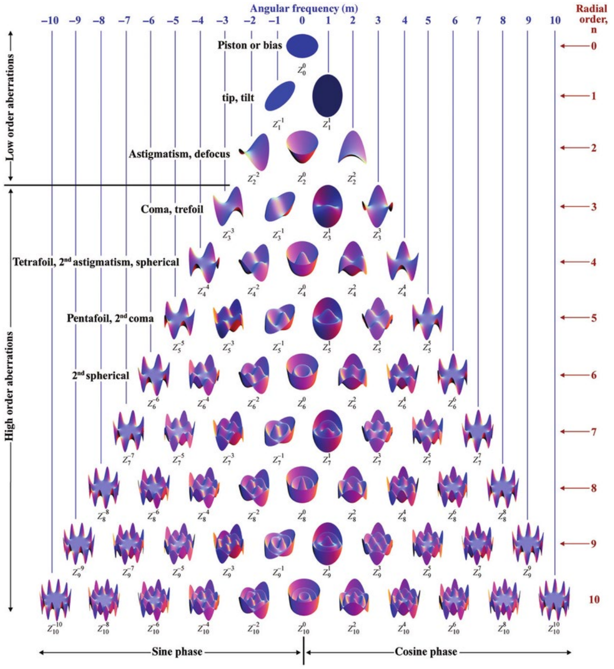


Fig.2 Surface plots of the Zernike polynomials up to 10 orders. The name of the main aberration is associated to the respective order. [3]

The spectrometer of PRISMA SG

High spatial and spectral resolution instruments changed our way of considering and understanding the environment in which we live and its main phenomena and characteristics. In fact, Earth surface observation is one of the most common and important space applications.

On this respect, the Italian Space Agency launched the PRISMA (PRecursore IperSpettrale della Missione Applicativa), a satellite designed and realized by Leonardo S.p.A. dedicated to the observation of the Earth surface, its natural resources and relevant natural processes. The satellite is composed by a hyperspectral sensor that acquires both VNIR (Visible and Near-Infrared) and SWIR (Short-Wave Infra-Red), and a panchromatic camera allowing to capture not only the geometry of the observed object but also the chemical-physical composition of the surface.

PRISMA is now observing the Earth surface from a LEO orbit at 615 km with a spatial scale of 30 meter/pixel over a field of view of 30 km [5]. In Fig. 3a the optical layout of the spectrometer is represented.

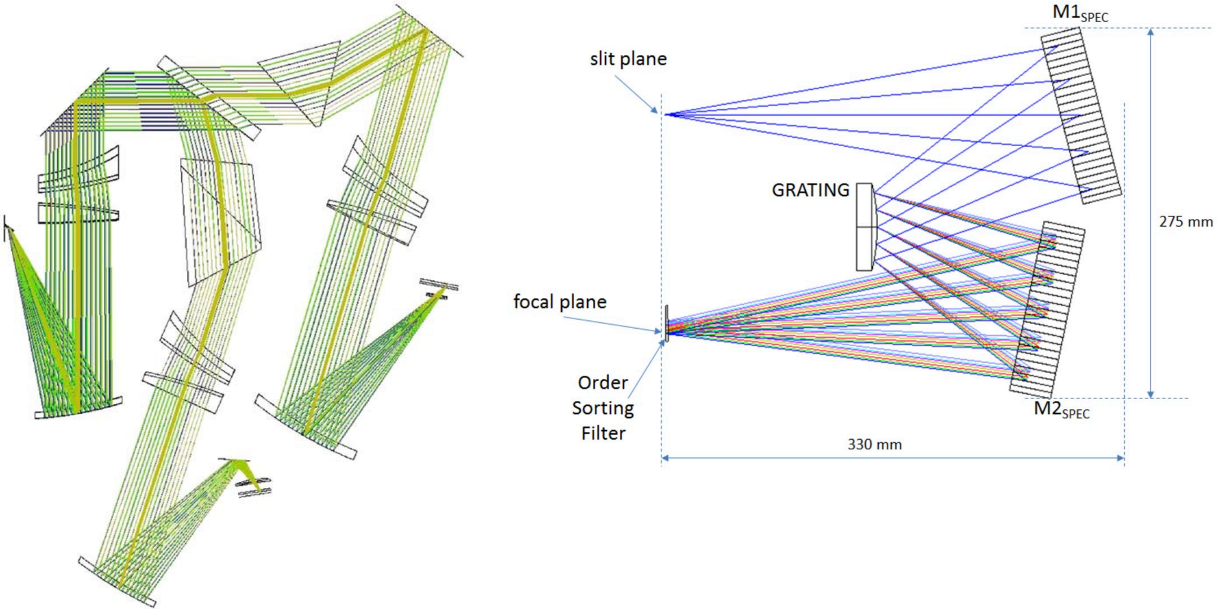
Now, entering more in depth of what this project concerns, we are working on the design and manufacturing of the first freeform optical element in Leonardo S.p.A., that will be integrated in the PRISMA SG, which yields a spatial scale improved of a factor 3 respect to the original PRISMA instrument: 10 meter/pixel over a view of 30 km (from an orbit of 520 km).

These very high performances will be reached thanks to the use of two identical Offner spectrometers using freeform optics (preliminary layout shown in Fig. 3b). The introduction of freeform mirrors to the Offner configuration enables to increase the FOV maintaining a good distortions correction thanks to the great flexibility offered by the increased number of degrees of freedom.

Presently, the spectrometer provides a good correction for smile and keystone distortions maintaining a good optical quality over the whole FOV and spectral range, as expected.

During the optimization phase we also studied different kinds of polynomials (Zernike, Chebyshev, XY) in order to understand which should be the best compromise in terms of computational weight and performance. From literature, we understood that the application of different polynomials is related to the pupil shape [1]. In our case, even if the spectrometer pupil will be annular (due to the pupil of the instrument telescope) the footprint of the different fields on the mirrors are overlapped enough to cover all the mirror surface, so we compared only the surface description with the Zernike Standards and the Chebyshev polynomials. We concluded that there are not many differences in terms of performances and number of variables, so we decided to adopt the Zernike ones.

Moreover, we are working on understanding the correlation between a perturbation of one of the instrument parameters (starting from position and tilts of the freeform mirrors) and the variation of the optical quality of the spectrometers.



(a) (b)

Fig.3: (a) PRISMA VNIR/SWIR spectrometer layout [5]; (b) PRISMA SG spectrometer layout where M1 and M2 are freeform.

Conclusions

The development of PRISMA SG spectrometer involving freeform mirrors represents a challenge from the theorical point of view. In this work, a preliminary design of the optical layout and the main objective in terms of performances have been presented. A short overview of the complex world of freeform surfaces is presented: a description of the main advantages of this technology in terms of performance and compactness has been introduced as well as the main difficulties that it is necessary to face for their design, manufacturing and testing.

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