ADVANCED OPTICAL FREEFORM DESIGNS FOR OHB'S NEW SPACE MISSIONS

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ABSTRACT

Freeform optics are widely acknowledged to be a game changer for future space missions and instruments: they allow a better performance with a reduced number of optical elements, in a smaller volume and with lower mass. Moreover, freeform optical designs bear a high potential to substantially cut the time required for integration and alignment of instruments. In short, time and cost from initial design to final space readiness will significantly be reduced by introducing freeform surfaces into optical space instruments.

Their fields of application are predominantly Earth observation, planetary and astronomy missions as well as laser communication terminals. Size can vary from CubeSat level instruments to large high-end space telescopes. In principle, they can cover all applications from thermal and short-wave infrared (TIR and SWIR) down to shorter wavelength systems in visual and UV. Most beneficial will freeform optics be for instruments like hyperspectral, multi-spectral (e.g. for CO2 and/or CH4 monitoring) or thermal infrared high-resolution ground imagers as well as for instruments requiring a large field-of-view. This paper gives insight into OHB's in-house freeform optics design tool chain and presents exemplary freeform designs.

1 INTRODUCTION

Freeforms are optical surfaces with an arbitrarily high amount of geometrical degrees of freedom, having in general no axis of symmetry. They represent refractive and reflective surfaces that differ significantly from spherical and aspherical geometries. This aspect is schematically illustrated in Figure 1.

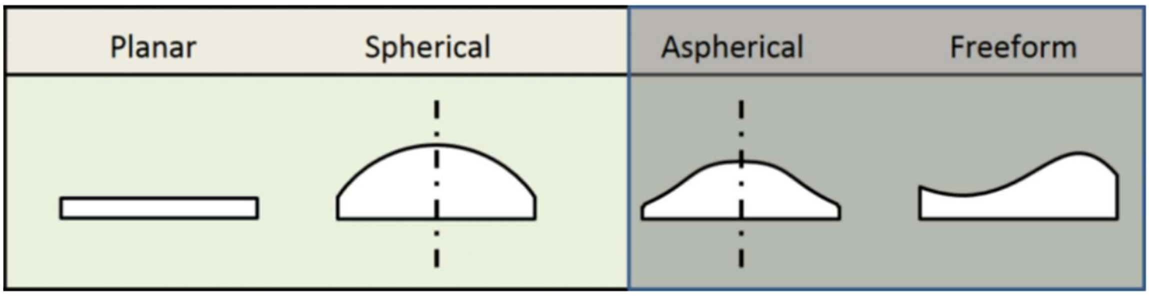

Figure 1: Comparison of different types of optical surfaces including freeforms.
Credit: Apple Inc [1]

Among many other applications (medical, lithography, automotive lighting, …), future space-based Earth observation, science, and exploration missions are ideal for their implementation, since they typically request high(er) optical performance within small(er) volume. In particular, industrial and commercial space markets ask for smart solutions at competitive cost and fast(er) time to space.

The application of freeform optics allows the designer to explore a larger solution space by:

- Increasing the field of view
- Reducing the volume
- Improving the image quality
- Reducing the number of optical elements

Volume reduction factors up to 50 are achievable by introducing freeform mirrors instead of classical spherical shapes as shown in Figure 2.

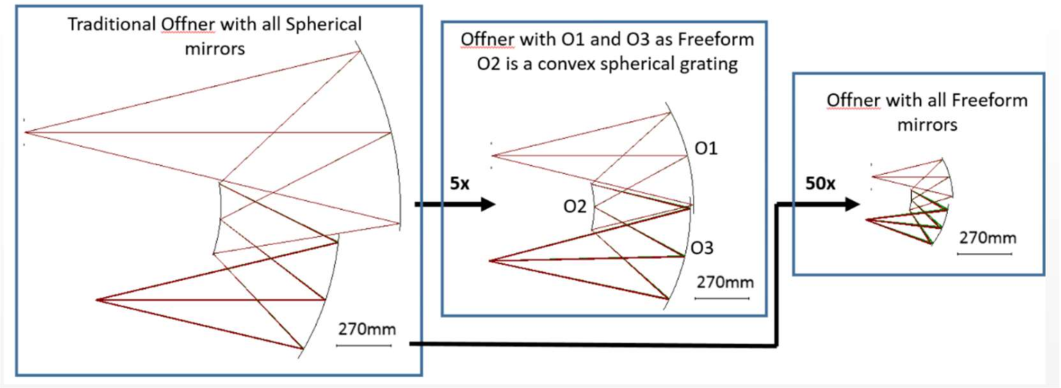

Figure 2: Example of reducing the volume of an Offner spectrometer by a factor of 50 by introducing freeforms in all mirrors/gratings. Credit: NASA [2]

Another example illustrating the achievable shrink of volume is shown in Figure 3, comparing the – non-space – application of a classical projector with traditional lenses and an ultra-compact modern projector, which can be placed very close to the wall or screen without visible distortion of the projected picture.

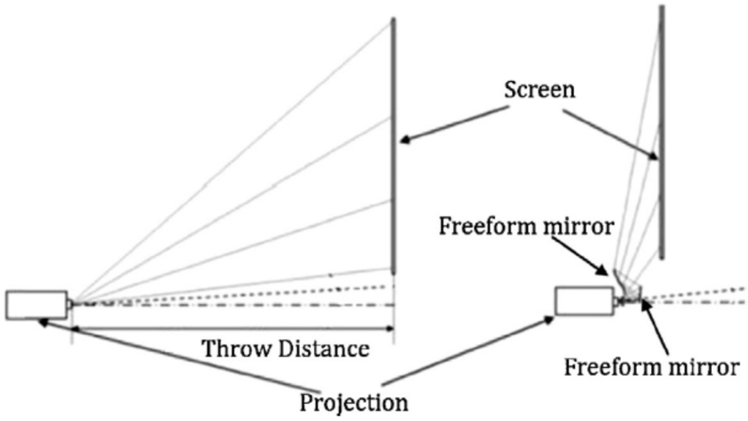

Figure 3: Slide projection in (left) classical configuration with large distance between projector and projection screen, and (right) modern version with embedded freeform optics to significantly decrease distance to screen without distorting the projected picture. Credit: [3]

2 DESIGN AND SIMULATION OF FREEFORM OPTICS

Mathematically, freeform surfaces are expressed as the classical conic term plus a series of polynomials such as Zernike, XY- or Q-polynomials, as shown in Eq. 1:

$$\boxed{z(r,\theta) = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{i=0}^{n} a_i P_i(r,\theta)} \tag{1}$$

Here, r is the radial coordinate, whereas a_i are the polynomial coefficients of a generic expansion series P_i (in cylindrical coordinates). This way, arbitrary, yet harmonic surfaces can be correctly expressed and therefore algorithmically simulated.

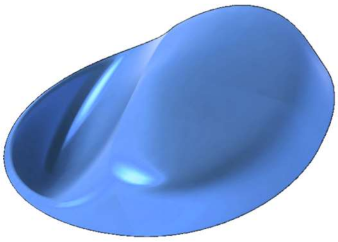

Figure 4: Mathematical representation (simulation) of a freeform surface. Credit: [4]

The existing limitations when doing freeform designs with the classical optical modelling and optimization tools like Zemax or Code V have recently been overcome by OHB System AG's advanced design tool chain. Essential part is OHB's proprietary freeform optics design software named "DORIS" that is based on algorithms for generalized differential ray-tracing [5].

With this tool chain, OHB now is a position to not only design freeform optics, but also correlate metrology results with the corresponding simulations and thus validate the specified optical performance (alignment, wave-front, line-of-sight, straylight etc.) in a precise, consistent and unambiguous way. The typical sequence of freeform design/verification steps is as follows:

1. Freeform optical design & analyses: company-internal ray tracing software ("DORIS") developed and coupled to commercial software tool Zemax
2. Freeform opto-mechanical design: fully integrated internal software tool chain, coupling optics and thermo-mechanics ("MultiPAS") [6]
3. Freeform surface manufacturing: co-operation with specialized manufacturing institutes and companies all over Europe
4. Freeform optics verification, alignment and integration: build-up of dedicated in-house integration stands and measurement equipment (see chapter 4).

3 CURRENT PROJECTS

The cutting edge optical design and engineering capabilities OHB can offer today allows to bring the freeform technology successfully into space: currently OHB is working on the design, machining, integration and characterization of two innovative freeform telescopes for a second-generation hyperspectral instrument, named Compact Hyperspectral Imager, and for a high-resolution TIR application, both compatible with CubeSats or MicroSats.

3.1 Compact Hyperspectral Imager Telescope

For the Compact Hyperspectral Imager (CHI) study, OHB is currently developing a telescope for multiple purposes. Its main use case is that of a slit-based hyperspectral imager of a push broom imaging system. With its extended field in along-track direction, it is also suitable for filter-based multispectral imaging. The telescope has the key parameters stated in Table 1. Further information about the telescope can be found in [7], in the same proceedings as this contribution.

Table 1: Key parameters of the Compact Hyperspectral Imager (CHI) telescope

Orbit Altitude [km]	*680*
Wavelength Range [µm]	*0.4 – 2.5*
Entrance Aperture Diameter [mm]	*150*
Telescope F-number [-]	*2.5*
Full Field of View Across Track [deg]	*6.48*
Full Field of View Across Track [deg]	*0.43*
Swath Width [km]	*77.0*
Ground Sampling Distance [m]	*26*
Volume [mm^3]	*440 x 250 x 250*
Mass [kg]	*16*

The preliminary CHI telescope design is shown in Figure 5:

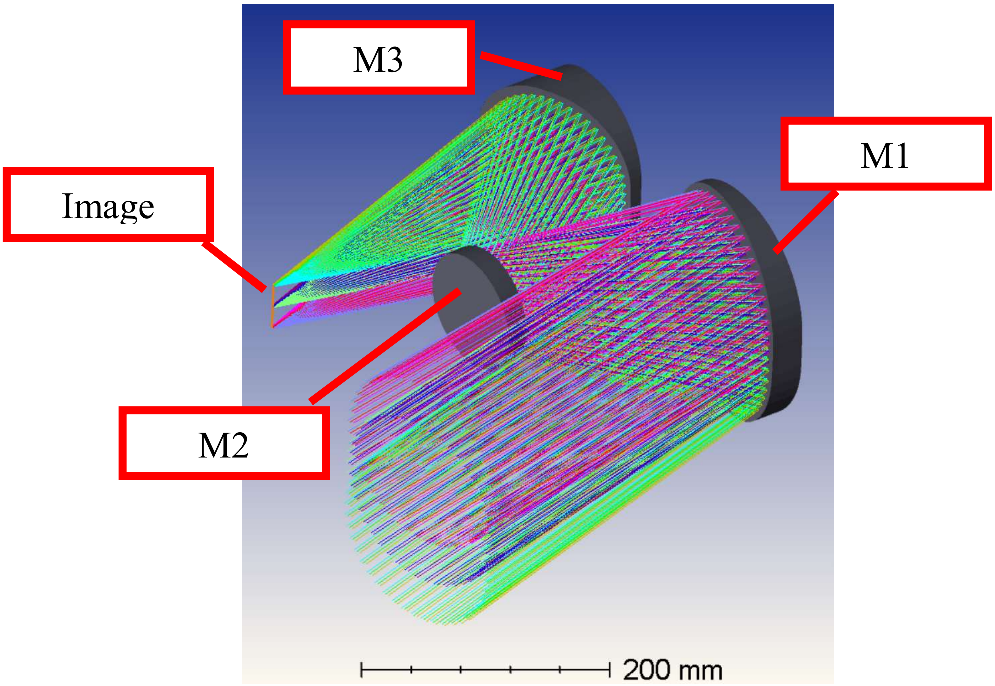

Figure 5: Preliminary CHI telescope layout

3.2 Thermal Infrared Imager Telescope

Since a few years, OHB is working on the development of a compact freeform Thermal Infrared (TIR) Imager telescope. The telescope is developed with the goal to fit within a 12 U CubeSat form factor, while maximizing the instrument aperture for high resolution imaging. Additionally, the Integrated Detector Cryocooler Assembly (IDCA) needs to fit within the volume. Overall, the TIR telescope has the key parameters listed in Table 2.

Table 2: Key Parameters of the Thermal Infrared (TIR) imager telescope

Orbit Altitude [km]	*500*
Wavelength Range [µm]	*10 - 12*
Entrance Aperture Diameter [mm]	*140*
Telescope F-number [-]	*2.4*
Full Field of View Across Track [deg]	*3.3*
Full Field of View Across Track [deg]	*0.38*
Swath Width [km]	*30*
Ground Sampling Distance [m]	*22*
Volume [mm^3]	*200 x 200 x 300*
Mass [kg]	*10*

These constraints result in a rather unconventional optical design that utilizes the capabilities of freeforms to its fullest: the infrared radiation enters through the aperture that also acts as stop. Via the two freeform mirrors M1 and M2, the scene is imaged onto the detector. Thereby, the two freeform mirrors are tilted in all three directions that, after folding of the optical path with fold mirror F1, sufficient length in x-direction is available for the IDCA. The two freeform mirrors make this concept without any symmetry planes feasible. The TIR telescope layout is shown Figure 6. The telescope is currently in manufacturing and first performance results are expected in the second half of 2022.

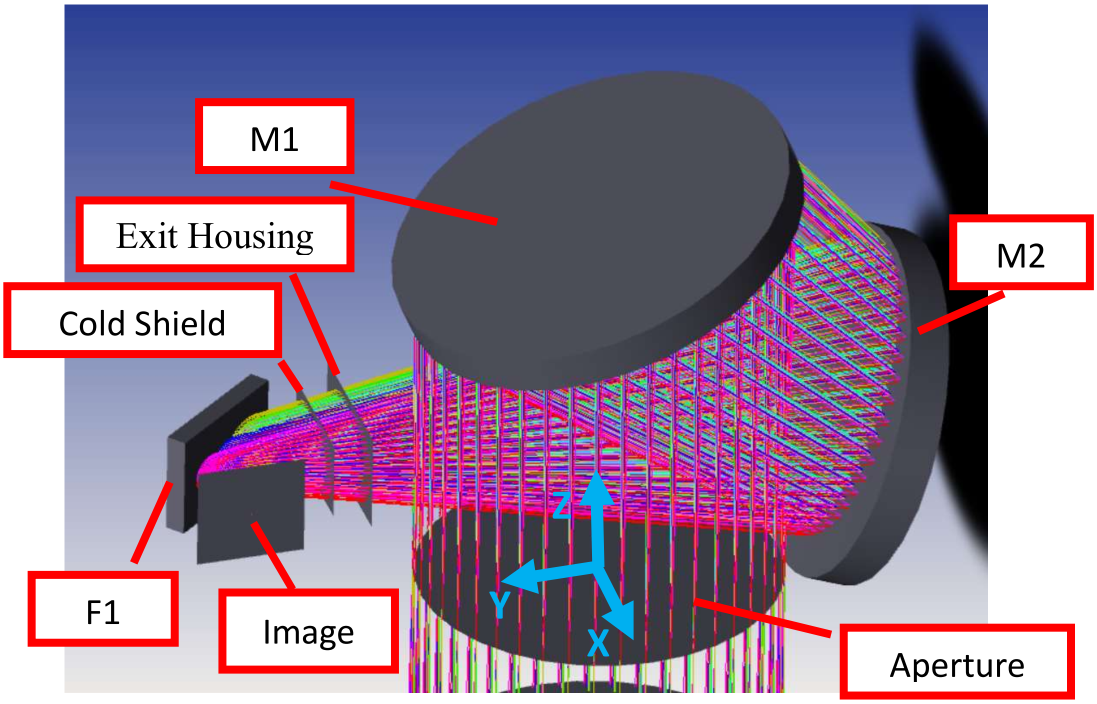

Figure 6: Preliminary TIR telescope layout

4 TEST AND VERIFICATION

For freeform optics, a particular challenge is the testing and verification of the individual optical surfaces. They can be measured with tactile measurements or with computer generated holograms (CGH) within an interferometric setup. For the above described telescopes, we utilize multiple methods for cross-verification, while considering the CGH measurements as most precise and holistic. The CGH measurement is performed with a setup like illustrated in Figure 7: a Fizeau interferometer with reference sphere illuminates through a CGH the freeform mirror. The CGH adjusts the optical path differences such that the deviations from a reference sphere are compensated and the interferometer can visualize the deviations from the designed freeform surface. Multiple freeform surfaces may be measured simultaneously. In parallel, additional alignment marks can be observed interferometrically such that the orientation of the surface to relevant alignment features is determined (Figure 8).

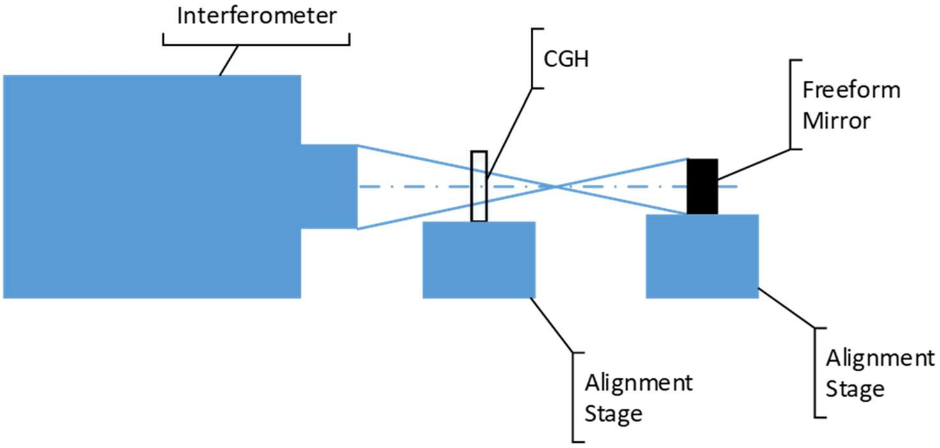

Figure 7: Typical test setup for freeform mirror verification

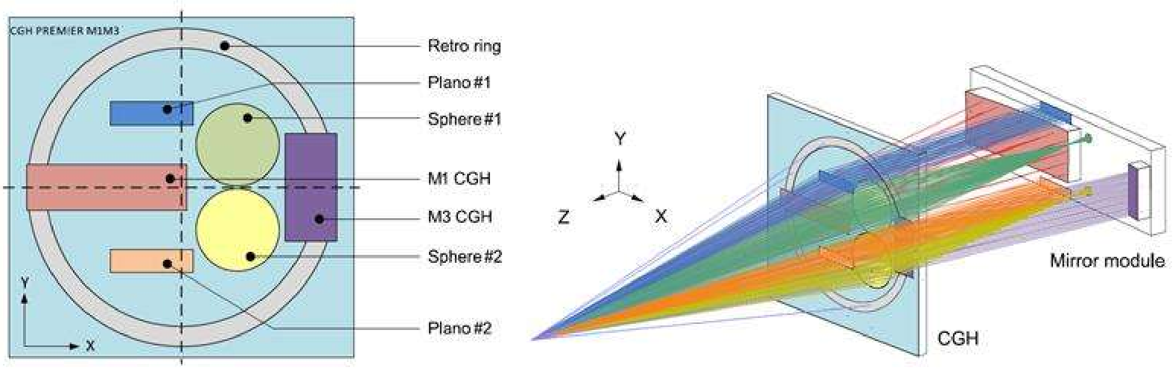

Figure 8: Optical layout of a Computer Generated Hologram (CGH) for testing mirror pairs and the measurement of alignment features. Credit: [8]

5 SUMMARY

It is widely agreed that (nearly all) future Earth observation, science and exploration space missions will request higher optical performance within smaller volume. In particular, institutional and commercial space markets ask for competitive cost and fast time to space. Freeform optical designs are a game changing and enabling key technology to meet these needs.

For many years, OHB has built up capabilities to design, simulate, manufacture (with partners), and verify freeform optics, primarily for space applications. Two reference projects are currently under realization: the Compact Hyperspectral Imager and Thermal Infrared Imager. Further targets for technology optimization are:

- Simulation and optimization of OHB's in-house software tool chain for freeform design
- Consequently follow a "design for manufacturability" approach
- Provide dedicated metrology for in-house testing, characterization, and verification
- Implement fast alignment methodology and tools
- Gain further hardware heritage and foster partnerships with manufacturers

Finally, it should be mentioned that OHB's freeform optics know-how and experience is open for collaboration and as engineering service to third parties.

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