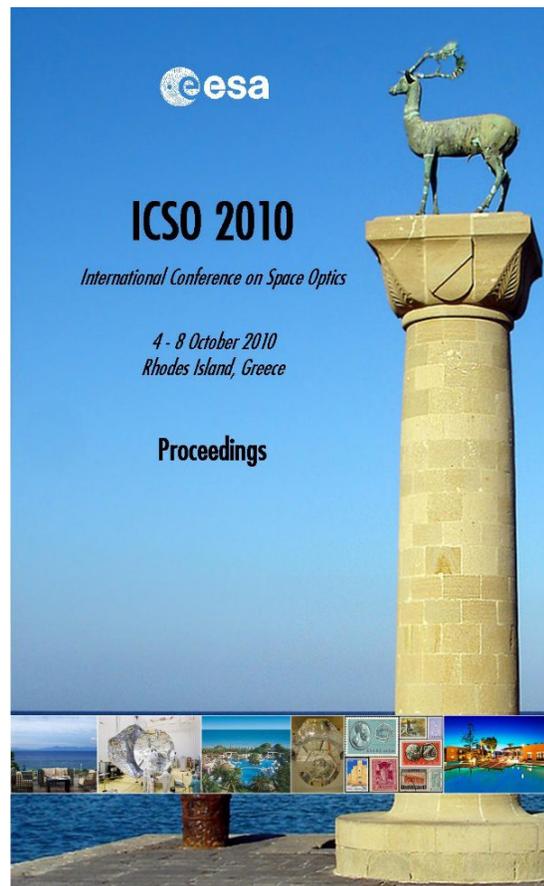# International Conference on Space Optics—ICSO 2010

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Effects of thermal deformation on optical instruments for space application

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EFFECTS OF THERMAL DEFORMATION ON OPTICAL INSTRUMENTS FOR SPACE APPLICATION

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ABSTRACT

Optical instruments for space missions work in hostile environment, it's thus necessary to accurately study the effects of ambient parameters variations on the equipment.

In particular optical instruments are very sensitive to ambient conditions, especially temperature. This variable can cause dilatations and misalignments of the optical elements, and can also lead to rise of dangerous stresses in the optics. Their displacements and the deformations degrade the quality of the sampled images.

In this work a method for studying the effects of the temperature variations on the performance of imaging instrument is presented. The optics and their mountings are modeled and processed by a thermo-mechanical Finite Element Model (FEM) analysis, then the output data, which describe the deformations of the optical element surfaces, are elaborated using an ad hoc MATLAB routine: a non-linear least square optimization algorithm is adopted to determine the surface equations (plane, spherical, n^{th} polynomial) which best fit the data. The obtained mathematical surface representations are then directly imported into ZEMAX for sequential raytracing analysis. The results are the variations of the Spot Diagrams, of the MTF curves and of the Diffraction Ensquared Energy due to simulated thermal loads.

This method has been successfully applied to the Stereo Camera for the BepiColombo mission reproducing expected operative conditions.

The results help to design and compare different optical housing systems for a feasible solution and show that it is preferable to use kinematic constraints on prisms and lenses to minimize the variation of the optical performance of the Stereo Camera.

I. INTRODUCTION

The BepiColombo mission is the cornerstone n. 5 of the European Space Agency (ESA); it consists of the Mercury Planetary Module (MPO) realized by the European Space Agency (ESA) and the Mercury Magnetospheric Module (MMO) realized by the Japanese Aerospace Agency (JAXA). The MPO will be devoted mainly to the remote sensing observations and its orbit will be slightly elliptical with a periherm of 400 km and the apoherm at 1500 km; the MMO will observe mainly the exosphere, the magnetosphere and the interplanetary medium and its orbit will be more elliptical with a periherm at 400 km and the apoherm at 11800 km.

The BepiColombo integrated observatory-system (SIMBIO-SYS) selected for the mission is dedicated to the geologic exploration of Mercury's surface, to resolve the spectroscopic features diagnostic of rock forming minerals and it will be mounted on the MPO [1]. The MPO orbital characteristics are mainly determined by the need for the remote sensing and the gravity field measurement to have high spatial resolution not changing too much all over the surface during the one year nominal mission lifetime, and they are extremely challenging due to the thermal constraints on the S/C (spacecraft). For a continuous observation of the planet surface during the mission, the S/C is 3-axis stabilized with the Z-axis, corresponding to payload boresight direction, pointing to nadir.

II. SIMBIO-SYS

SIMBIO-SYS consists of a suite of integrated sensors, including the Stereoscopic Imaging Channel (STC) with broad spectral bands in the 400–950 nm range and medium spatial resolution (up to 50 m), the High Resolution Imaging Channel, (HRIC) with broad spectral bands in the 400–900 nm range and high spatial resolution (up to 5 m) and the Visible and near-Infrared Hyperspectral Imaging Channel (VIHI) with high spectral resolution (up to 6 nm) in the 400–2000 nm range and spatial resolution up to 100 m. The geomorphological information provided by STC will therefore allow the identification of different features within the larger footprint of VIHI, helping the interpretation of the hyperspectral spectrum of the mixed signal in VIHI pixel.

A. THE STEREOSCOPIC IMAGING CHANNEL (STC)

STC [2] is a double wide angle camera designed to image each portion of the Mercury surface from two different perspectives, providing panchromatic stereo image pairs required for reconstructing the Digital Terrain Model (DTM) of the planet surface. In addition, it has the capability of imaging some portion of the planet in four different spectral bands.

The main scientific requirement for the STC is to provide the surface global map in stereo mode of the surface and secondly to study selected areas in predefined spectral bands.

The adopted telescope optical solution (see Fig.1) is a novel design, in which a couple of rhomboid prisms redirect the ±20° wide open beams along directions much closer to the system optical axis.

After the two prisms, a modified Schmidt telescope follows, in which a correcting doublet positioned at about half distance between the spherical mirror M1 and its center of curvature replaces the classical Schmidt correcting plate. Finally, a field correcting system has been included just in front of the detector.

The nominal FoV of each sub-channel is 5,3°x4,5° subdivided in 3 narrow strips, one for each filter, covering three quasi-contiguous areas on Mercury surface.

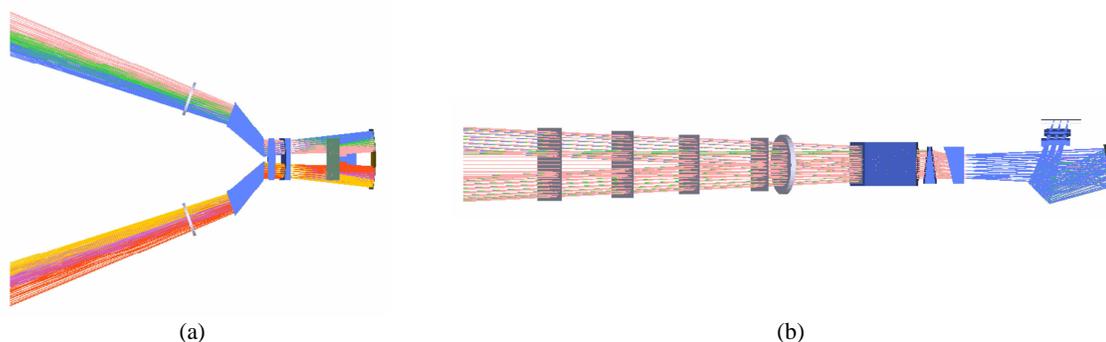(a)   (b)

Fig. 1. Ray-trace scheme of the Stereo Camera of BepiColombo mission: (a) top view; (b) left view.

STC mechanical accommodation (design see Fig.2) has to take into account the peculiar thermal environment at which STC will be subjected in its orbiting around Mercury. The planet is very near to the Sun, and this fact has an impact on the temperature's variations during the instrument's operation, i.e. the expected temperatures range is relatively high (between -20 °C and +30 °C). In order to make the system performance as much as possible independent from the temperature variations, the two mirrors will be made of Aluminum Alloy 7075-T6, the same material of the STC structure [3].

The prisms and the lenses will be made of Fused Silica radhard glass; the reflection of the beam inside the prism takes advantage of the total internal reflection at the glass-air interface.
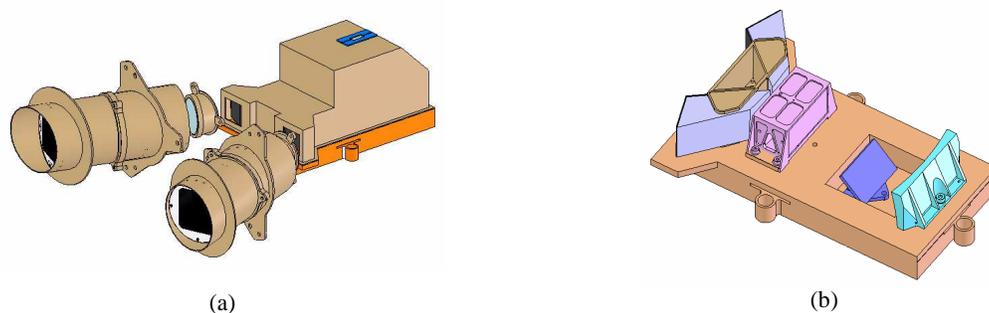

(a)   (b)

Fig. 2. Mechanical design of the Stereo Camera of BepiColombo mission.

The Fused Silica optics (lenses and prisms) of the Stereo Camera can be glued on the structure in eight points near their vertices or kinematically constrained. In choosing mounting configuration for optical elements, it is better to observe the basic principles of kinematics [4]. A body in space has six degrees of freedom (or ways in which it can move). A body is fully constrained when each of these possible movements is singly prevented from occurring.

One of the critical aspects of a glass to metal bond is the dissimilarity of coefficients of thermal expansion for the materials bonded. This fact can lead to rise dangerous stresses on the optics. For this reason various types of flexures are commonly used to mount optical components.

The kinematic constraints for the prisms and the lenses of the Stereo Camera have been designed as curved beams that act like springs to avoid the fracture of the optical elements (see Fig.3).
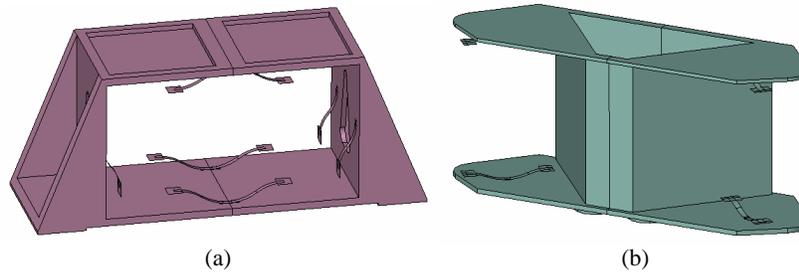

(a)   (b)

Fig. 3. Example of kinematic constraints applied to the housing systems of the lenses (a) and prisms (b).

III. IMPACT OF THE THERMO-ELASTIC EFFECTS ON THE STEREO RECONSTRUCTION

The optical instruments are very sensitive to temperature's variations, because those variations can change the distances and inclinations between the optics, cause element's misalignments and surface deformations. This fact can reduce the performance of the camera in terms of Diffraction Ensquared Energy, MTF curves and Spot Diagrams.

A new method to determine the influence of thermal loads on space instrument optical performance is presented, the flow chart of the method is depicted Fig.4.

This method has been directly applied to determine the influence of thermal loads on STC performance and can be summarize in some steps:

- thermo-elastic analysis is performed introducing the constraints and the thermal loads;
- the results of Finite Element Analysis (FEA) are elaborated to determine the mathematical equation which correctly fits the shapes of the deformed optical surface. In this process great care has to be taken in converting FEA units to optics units and converting results in the appropriate optical coordinate systems;
- the optics mathematical formulas are imported in a ray-trace code, like ZEMAX, to determine Spot Diagrams, MTF curves and Diffraction Ensquared Energy.
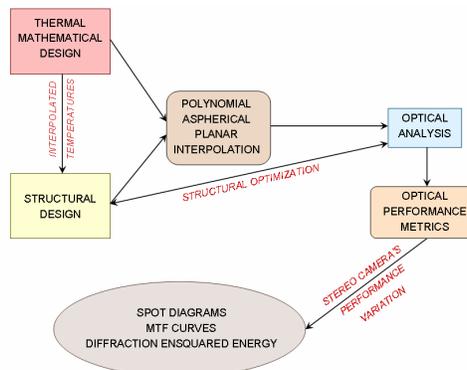

Fig. 4. Scheme of the method to study the changing in optical performance due to thermo-elastic analysis.

In the next paragraphs are exposed all the details of this method.

A. Thermo-elastic analysis

The finite element analysis (FEA) of the Stereo Camera has been performed to determine the deformations of the optics due to thermal loads. It has been considered an integration temperature $T_i = 20$ °C and the analysis has been done at two different temperatures: the lowest temperature of the operative range, $T_f = -20$ °C, and the highest one, $T_f = 30$°C; the results at $T_f = -20$ °C are showed in Fig.5.

FEM outputs can be separated into two parts: rigid body motions of optics, which describe the translations of the center of each optical element, and elastic distortions, that are deformations of the surfaces of the element which are typically described as polynomials, aspheric or planar surfaces.
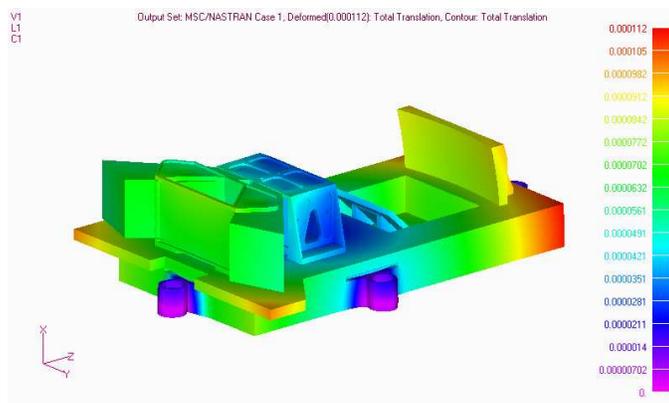
Fig. 5. Results of thermo-elastic analysis from integration temperature $T_i = 20°C$ to temperature $T_f = -20°C$.

B. Surfaces interpolation based on Non linear Least Square algorithm

An algorithm based on Non-linear Least Square Data Fitting has been used to determine the mathematical equations of each surface. This is the form of least squares analysis which is used to fit a set of points with a model that is non-linear. It is used in some forms of non-linear regression.

The basis of the method is to approximate the model by a linear one and to refine the parameters by successive iterations. A set of m data points, (x_1, y_1, z_1), (x_2, y_2, z_2), …, (x_m, y_m, z_m), and a curve (model function) $z = f(x_i, y_i, \beta)$, that in addition to the variables x and y also depends on n parameters $\beta = (\beta_1, \beta_2, …, \beta_n)$, are considered. The aim of the optimization process is to find the vector β of parameters such that the curve best fits the given data in the least squares sense, that is, the sum of squares is minimized:

$$S = \sum_{i=1}^{m} r_i^2 \tag{1}$$

where the residuals (errors) r_i are given by:

$$r_i = z_i - f\left(x_i, y_i, \beta\right) \tag{2}$$

for i = 1, 2, …, m.

In Fig.6 it is possible to see an example to compare the real optics shape with the calculated sag and the residual of the computing for the front surfaces of one of the Stereo Camera lenses. As mentioned before, the results are the variations of optical parameters as a consequence of the thermal loads and optics constraints.
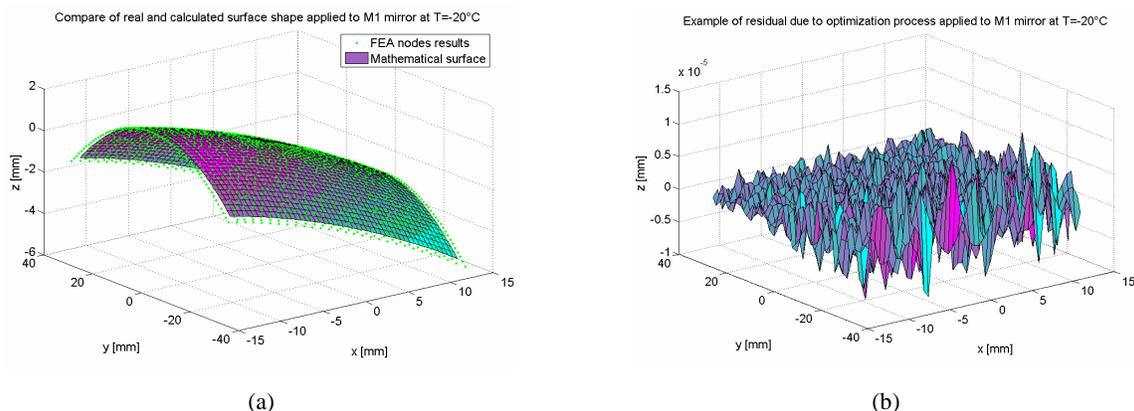

(a)   (b)

Fig. 6. Example of surface interpolation using Nonlinear Least Square algorithm applied to the shape of M1 mirror: (a) surface interpolation; (b) residuals.

IV. RESULTS

The results show that, considering bond constraints, the most critical optical elements are the prisms; their movements and surface deformations decrease telescope's performance in terms of MTF, Diffraction Ensquared Energy and of Spot Diagrams, their size become larger and their coordinates on the detector translate.

Using kinematic constraints is very important to preserve Stereo Camera's performance at different temperatures; in this case the worst condition, in terms of optical performance decreasing, is determined by the translations and deformations of the two mirrors. The results of the themo-elastic analysis in terms of Spot Diagrams, MTF curves and Diffraction Ensquared Energy have been treated considering bond and kinematic constraints. The use of bond constraints causes a consistent deformation of the optics and the translation of the spots of the images (see Fig.7): the central spot moves of $\Delta P = (-0,3$ px;16,5 px$)$ in the detector reference system. In Fig.8 it is possible to see the resulting Diffraction Ensquared Energy, it decreases to $EE_{min} = 1,41\%$, and the corresponding MTF curves.
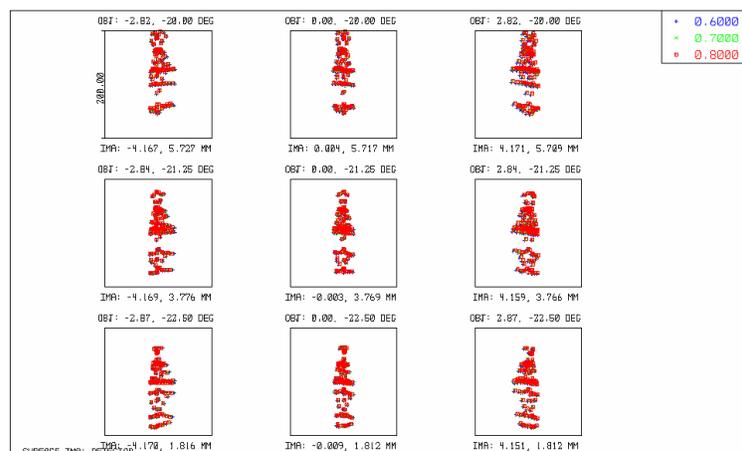

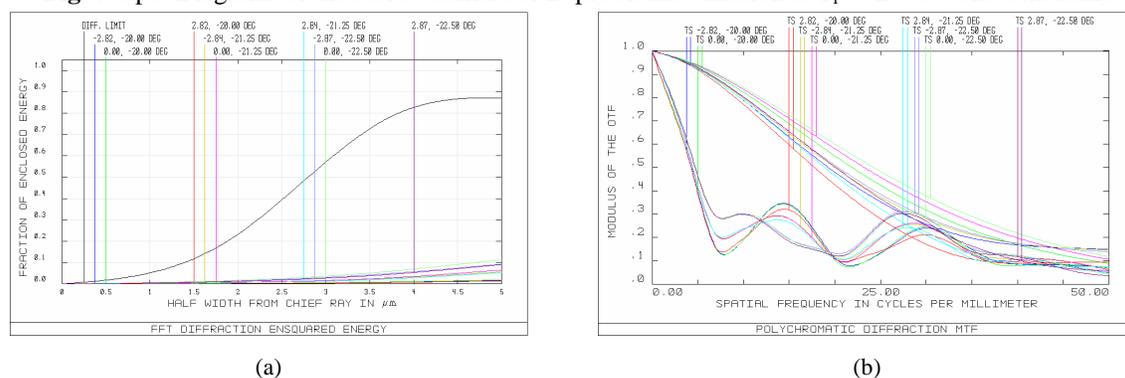**Fig. 7.** Spot Diagrams of the Stereo Camera of BepiColombo mission at $T_f = -20°C$: bond constraints.

(a)   (b)

Fig. 8. Diffraction Ensquared Energy (a) and MTF curves (b) of the Stereo Camera of BepiColombo mission at $T_f = -20°C$: bond constraints.

In Fig.9 the Spot Diagrams obtained for the kinematic constraint solution is reported: the spot's dimension is unaltered and the translation is smaller $\Delta P = (-4,2$ px;1,2 px$)$. In Fig.10 the resulting Diffraction Ensquared Energy, that changes from EEmin = 79,83% to EEmin = 78,80%, and the MTF curves are showed.
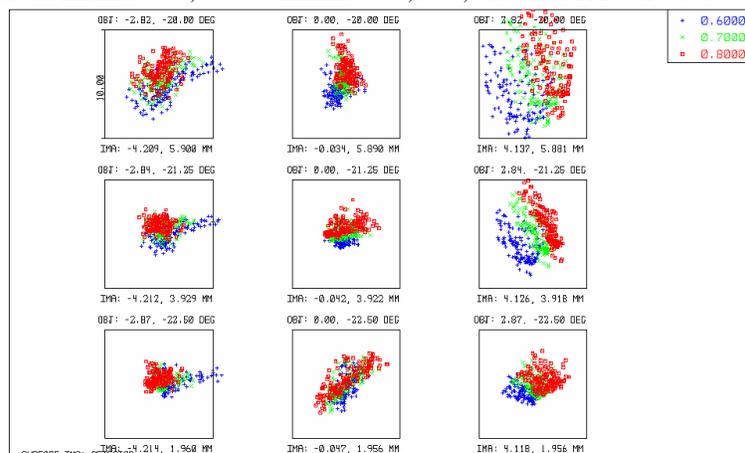

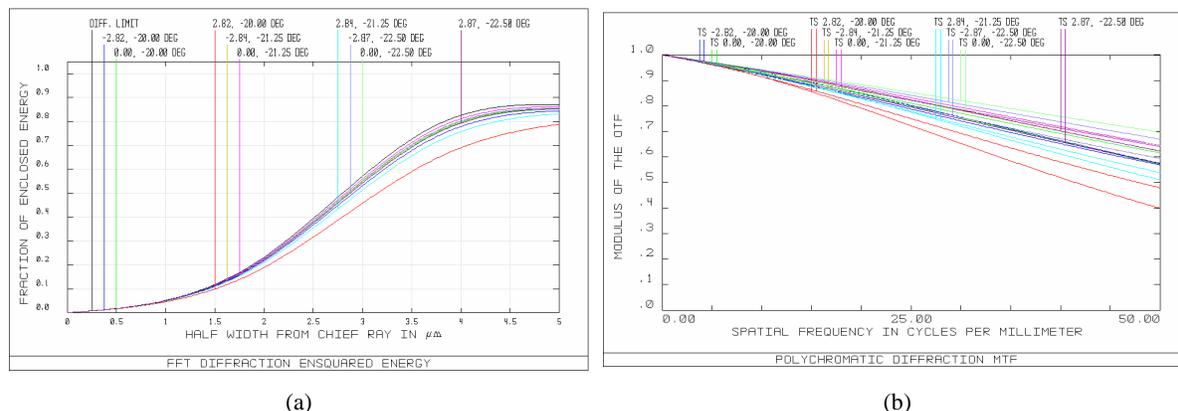**Fig. 9.** Spot Diagrams of the Stereo Camera of BepiColombo mission at $T_f = -20°C$: kinematic constraints

(a)   (b)

Fig. 10. Diffraction Ensquared Energy (a) and MTF curves (b) of the Stereo Camera of BepiColombo mission at T_f = -20°C: kinematic constraints.

CONCLUSIONS

A new method to determine the mathematical equations of the deformed optical elements surfaces, after the thermo-elastic analysis, and to import the results in a raytracing software named ZEMAX has been presented.

As a consequence of the optical misalignment there are variations of the Spot Diagrams, Diffraction Ensquared Energy and the MTF curves of the telescope.

The thermo-elastic analysis of the Stereo Camera for the BepiColombo mission, done with the NASTRAN code, has been described; the variations of the optical performance induced by the FEA deformations have been fully investigated by raytracing analysis.

The results show that it is preferable to use kinematic constraints on prisms and lenses to minimize the variations of the optical performance.

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