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DESIGN, MANUFACTURING AND ALIGNMENT OF A FLUORESCENCE IMAGING SPECTROMETER BASED ON REFRACTIVE OPTICS AND A TRANSMISSION GRATING

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I. INTRODUCTION

In the framework of the Fluorescence Explorer (FLEX) phase A/B1 study, an elegant breadboard (EBB) of an imaging spectrometer is designed, manufactured and aligned by AMOS, with Airbus Defence&Space as the prime Contractor of the study. The FLEX mission is one of the two candidates of the 8th Earth Explorer mission. The main constituting instrument of the FLEX mission is an imaging spectrometer observing vegetation fluorescence and reflectance with a high- and a low-resolution channels in the 500 nm -780 nm band. As part of the system feasibility study of the mission, a breadboard of the high-resolution channel of the instrument is designed and manufactured with a high representativeness of a future flight concept. The high-resolution channel is referred to as FIMAS (Fluorescence IMAging Spectrometer). The main purpose of the EBB is to demonstrate (1) the manufacturability of the instrument and (2) the compliance of the optical performances with respect to the science requirements (including spatial and spectral resolution and stray-light).

In this project, AMOS was in charge of the opto-mechanical design, manufacturing, integration and alignment of the instrument. Moreover, image quality tests were developed as acceptance checks of the instrument before the system performance test campaign that was carried out by Airbus D&S.

In order to meet the requirements for the FIMAS EBB, an innovative design approach has been adopted. This approach is based on the need for a straightforward alignment of the instrument that mostly relies on manufacturing tolerances and mechanical measurements with a 3D Coordinate Measuring Machine (CMM). The design makes use of the most up-to-date manufacturing and metrology techniques, while remaining compatible with standard capabilities in the European space industry.

The main requirements for the FIMAS EBB are discussed in Section II. Then, the opto-mechanical design of the breadboard is exposed in Section III, and the alignment methods are detailed in Section IV. Section V presents the spatial resolution measurements of the instrument.

II. FIMAS SPECIFICATIONS

The requirements of the FIMAS EBB are listed in Table 1. They mainly focus on the spatial resolution and stray-light performances. The requested image quality is the main design challenge, all the more so a large survival temperature range needs to be taken into account. The stray-light performances are expressed in terms of a very low level of contamination of the optics. Such a contamination level is a key constraint for the definition of the AIV tasks.
The spectral performances are essentially driven by the quality of the transmission grating. In this part of the study, the transmission grating was provided by Airbus D&S to be integrated and aligned in the breadboard. Therefore, a requirement for the co-alignment of the grating lines to the slit axis is provided.

III. OPTO-MECHANICAL DESIGN

The FIMAS EBB is an on-ground demonstrator of a flight instrument concept. Whereas the FIMAS EBB is not expected to be submitted to an extensive environmental test campaign (test campaign only limited to optical performances and thermal cycling), a particular care has been brought to its design so as to reflect as closely as possible the real needs of a flight instrument. To this aim, a space-compatible approach has been followed-up throughout the design phase, with a specific emphasis on the lens supporting concept. While not extensively analyzed as should be a flight instrument, the EBB design provides a reliable baseline design for a future development of the flight instrument concept.

The FIMAS EBB assembly consists in the following parts:

1. an optical bench and its mounting I/F,
2. the lens barrels (incl. optics) and their support to the optical bench,

Table 1: Main requirements of the FIMAS EBB

FIMAS EBB main requirements	
Type of optical instrument	Refractive spectrometer with Telescope optics Collimator entrance slit Collimator optics Transmission grating Camera optics
Wavelength	677 nm – 780 nm
F-number	2.7
FoV	+/- 5.2° in across-track direction
Spatial resolution	RMS spot diameter in along-track < 10.6 µm RMS spot diameter in across-track < 21.5 µm
Spectral registration	co-alignment of the grating lines to slit axis < 100 µrad
Entrance pupil diameter	80 mm
Slit width in across-track direction	80 µm
Slit length in along-track direction	40 mm
Contamination level on optics	goal is 10 ppm
Environment	Operational T° of 20°C Survival T° range : [-40°C ; +60°C]

3. the collimator entrance slit,
4. the grating and its support, and
5. the aperture stop.

One of the common features of the opto-mechanical design of the FIMAS constituting elements is that they are designed in view of a fast and reliable alignment process that relies as much as possible on mechanical measurements and/or manufacturing tolerances. The use of optical measurements as a feedback for an iterative alignment process is minimized.

A. Optical Bench

The optical bench is a bulk Aluminum panel whose particular shape is optimized so as to minimize the gravity-induced deflection when loaded with all the sub-assemblies. The optical bench contains interfaces to the different FIMAS sub-assemblies. The I/F mounting planes exhibit a very tight tolerance of parallelism, so as to provide a correct orientation of the optical elements when they are mounted on the breadboard without the need of long, iterative and sometimes complex alignment methods.
The optical bench breadboard is not fully representative of what should be a flight bench. In particular, the choice of Aluminum might not fit with instrument mass requirements. However, the concept of I/F planes with machined inserts that are fixed on the optical bench is representative of a flight design.

B. Lens Barrels

The lens support of the FIMAS instrument results from a compromise between the following design drivers (not listed by order of precedence – all were considered with a similar importance):

1. The need for a fast and reliable integration & alignment procedure that is compatible with the contamination level requirements,
2. The accommodation of the lens-support thermal differential expansion that could irreversibly degrade the glass materials if not properly handled,
3. The lens alignment requirements to < 50 µm for both axial (z-axis) and lateral (x- and y-axis) positions, and
4. The stability of the lens position after thermal cycles (max -60° from integration temperature).

The FIMAS lenses are separated into three independent functional groups (telescope – collimator – camera). From this separation, it intuitively follows that (i) the lens groups should be independently integrated on the optical bench, and (ii) that all the lenses of a group should be assembled together in a common structure. This offers the possibility to align the lenses in two steps: (1) the lens internal alignment within a group and (2) the alignment of the lens assembly on the optical bench. This greatly facilitates the integration and alignment stability of the instrument. Moreover, the common structure that contains the lenses yields an efficient contamination control mean with adequate covers.

In order to keep the cleanliness level of the lenses very low, each group of lenses has to be integrated and aligned in less than 5 hours. It avoids using complex designs of the support (e.g. blades connected to pads that are glued on the lenses) and does not favor the individual alignments of the lenses with optical feedback (e.g. centering machine). These reasons lead us to consider cylindrical barrels with machined seats for the lens that mechanically define their position. With such a concept, the lenses are inserted in the barrel to their seats and their position is secured with a retaining ring (drop-and-secure approach), as shown in Fig. 1. For sake of an easy integration procedure, all lenses are secured with their own dedicated retaining ring.

The differential thermal expansion between the lenses and the barrel leads us to select the barrel materials such that it exhibits a CTE as close as possible to the lens materials CTE. The glass materials used for the FIMAS design have CTE values that match the CTE of Titanium. Therefore, Titanium appears as the most appropriate candidate for the barrel material.

Inside the barrel, the axial and lateral supports of the lens are decoupled. This decoupling involves the manufacturing of two flat surfaces on both sides of the lens. The bottom flat surface is positioned against shoulders that are accurately machined within the barrel (machining accuracy to 20 µm for position and 10 µm for perpendicularity with respect to the barrel axis). The very fine machining of the barrel shoulder associated to a very good knowledge of the lens vertex position defines the axial position of the lens within the barrel to 30 µm and the lens optical axis orientation to 0.4 arcmin without mechanical and/or optical alignment.
The lens axial position is secured with an axial pressure applied by a retaining ring that is screwed along the barrel inner bore. Because the retaining ring is pressed against a flat surface on the lens, there is no self-centration mechanism that is induced as it usually occurs when setting the axial pressure on spherical surface (the spherical surface is centered with respect to the retaining ring axis). This eliminates the needs of a very accurate and delicate machining of the retaining ring.
Although the CTE of the barrel almost matches those of the lenses, the differential expansion of the barrel with respect to the lens still needs to be taken into account and handled in such a way that the pressure set at the integration temperature (i) does not critically increase at colder temperatures and (ii) keeps securing the lens position at warmer temperatures. To this aim, it is necessary to include some flexibility in the retaining ring. This flexibility is obtained thanks to flexures that are embedded within the retaining ring. Because it matches the barrel CTE and provides very good mechanical strength, the retaining rings with flexures are also made in Titanium (see Fig. 1).

In addition to the axial stack that defines the position and orientation of the lens along the optical axis, the lenses are also radially maintained by a dedicated support that fixes the location of the lens with respect to the barrel axis. In order to provide a fast and reliable alignment process, the lens radial position is defined by mechanical references. As a result, the barrel inner bore diameter at the lens seat location is accurately machined and provides a mechanical reference of the barrel axis. The lens is integrated and aligned against this axis reference.

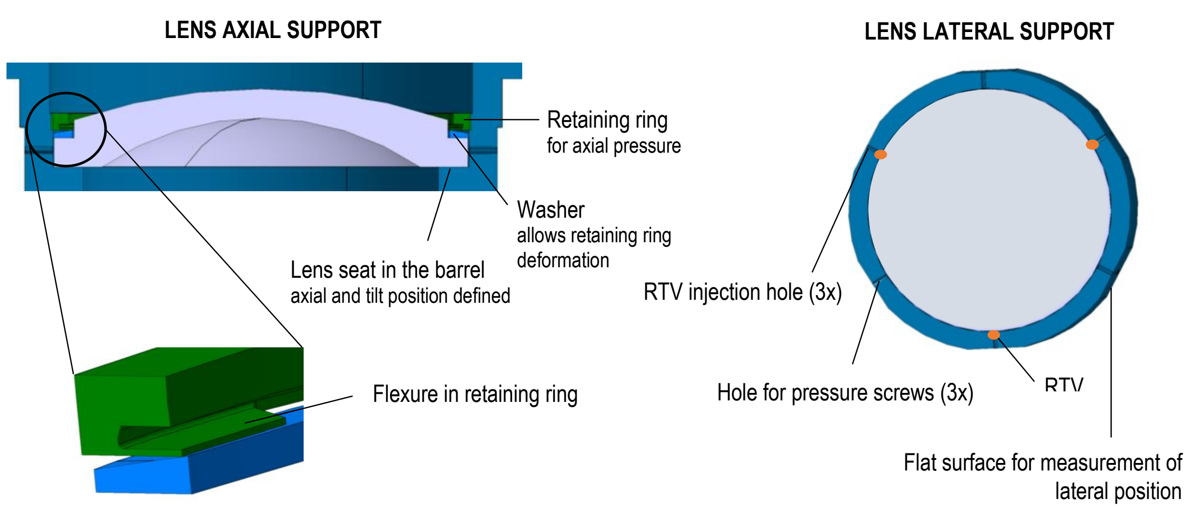

Fig. 1. Lens axial and lateral support

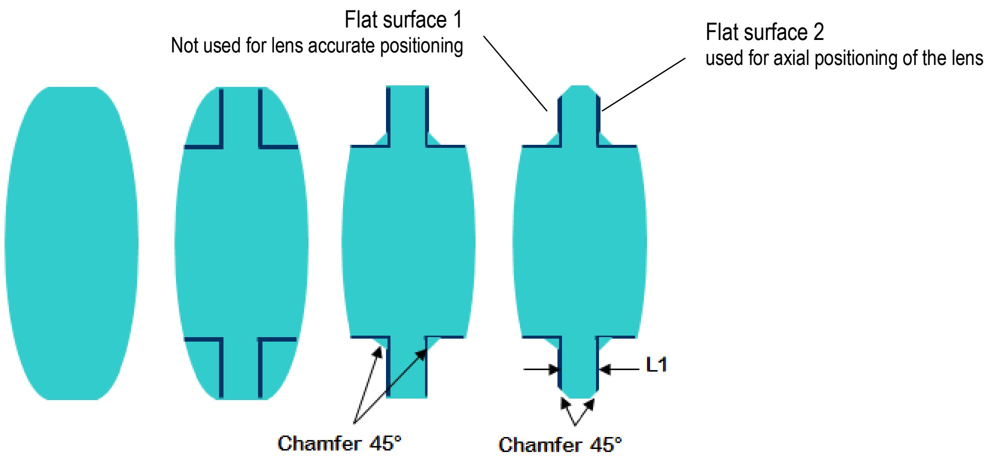

Fig. 2. Flat machining of FIMAS lenses

The radial positioning of the lenses is performed before the integration of the stack for the axial support. Once the lenses are aligned with respect to the mechanical references, the radial position of the lens is secured with pressure screws that are accessible from the barrel outer surface. The pressure screws maintain the radial position of the lens during the integration of the retaining ring.
Because of the radial thermal differential expansion between the lens and the barrel, the screws cannot permanently be used to fix the radial position of the lens. The increase of radial pressure at the coldest temperatures of the thermal cycles cannot be supported by the lens material. Neither could the radial support be totally removed so as to only rely on the friction forces developed by the axial support to maintain the radial position of the lens after thermal cycles or after being subjected to an unwanted lateral load (e.g. during transport). Therefore, in order to provide some resilience with sufficient retaining forces, the use of an RTV glue is the most appropriate solution. The glue is inserted at three locations around the barrel outer circumference. At ambient temperature, the post-cured RTV stiffness is able to prevent the lenses from leaving their nominal radial position. When the temperature varies from the ambient conditions, the RTV elastic properties are used to accommodate the radial differential expansion of the barrel with respect to the lens by an elastic deformation of the RTV spot.

The adopted lens support design has direct consequences on the physical shape of the lenses. While the center thickness, surface curvatures and optical clear aperture are constrained by the optical design and cannot be modified, the lens mechanical aperture and edge thickness can be optimized according to the barrel design that allows for an individual drop-and-secure integration with independent axial and lateral supports.
As a result, the lenses exhibit a non-conventional shape that is schematically sketched in Fig. 2. In particular, the outer rim of the lens is machined such that it exhibits two flat surfaces. The thickness of the lens between both flat surfaces is determined according to the available space within the barrel. The mechanical aperture is chosen so as to be compliant with (1) a sequential integration of the lenses in the barrel – starting from the smallest lens to the largest one, and (2) manufacturing constraints.
One of the flat surfaces is used to precisely locate the lens within the barrel and shall be manufactured with a sufficient accuracy so as to be compliant with the lens positioning budget. The opposite flat surface is only used for axial support and thus not necessarily need to be manufactured with identical tight tolerances. For stray-light mitigation purposes, the external zones around the edges of the lenses are blackened with a space-compatible black-marker whose thickness has to be kept at the level of 1 µm to not degrade the machined surface tolerances.

C. Mechanical Slit

The collimator entrance slit consists in a single Aluminum part in which the slit is directly machined (see Fig. 3). The supports also contains mechanical reference surfaces that are machined during the same step as the slit. It allows for a very accurate positioning of the slit with respect to the reference surfaces that are accessible for 3D coordinate measuring machine measurement when integrated on the bench. This highly facilitates the alignment of the slit to the telescope FP with a very good stability and reproducibility.

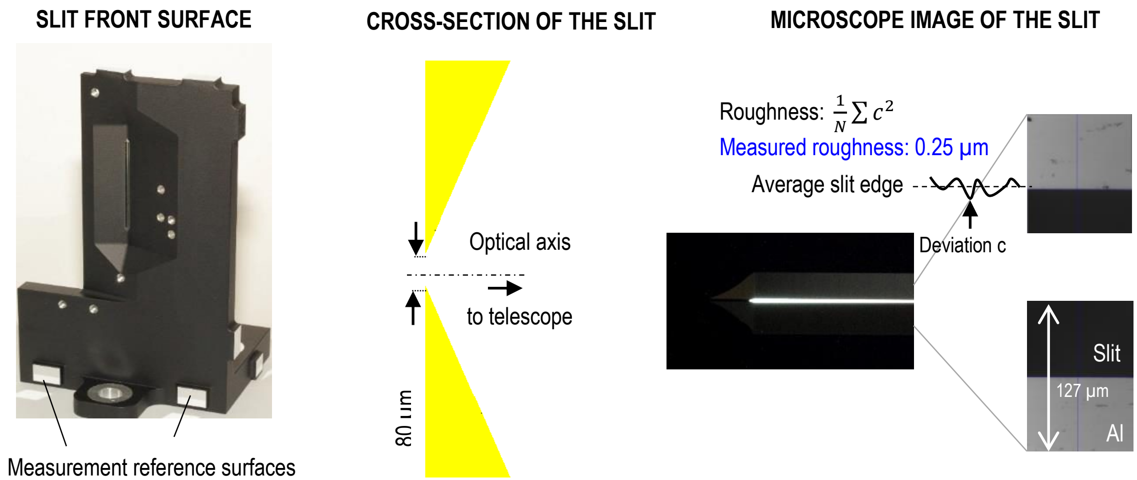

Fig. 3. Pictures of the mechanical slit and microscope view of the edge of the slit

The slit width is 80 µm as seen along the optical axis (see Fig. 3). The slit is located at the back surface of the support. The slit is machined from the front surface of the support. It is machined with a diamond-turning lathe machine, and is accurately referenced to the reference surfaces (better than 5 µm). The slit is shaped as a V-groove whose tips that are located at the back surface of the support defines the slit edges. The opening angle of the groove results in a compromise between stray-light mitigation purposes and machining constraints. The accuracy of the slit roughness is better than 1µm over the complete slit length (40 mm) and the slit width is controlled to +/- 1 µm.

D. Grating Support

The grating is supported in a bracket whose design adopts the same philosophy as that used for the barrel and slit supports, i.e. aluminum support with accurate machined reference surfaces that are used during the alignment. The grating is fixed to the bracket by three blades that are attached to three Invar pads directly glued on the grating edge. Because the spectral performances of the instrument require a co-alignment of the grating line to the slit axis, the grating support consists in two parts:

1. A fixed frame that contains the I/F planes toward the optical bench and the reference planes for the alignment, and
2. A removable frame on which is attached the grating (via 3 blades). This frame can be finely adjusted in rotation around the optical axis by two micrometer screws.

IV. ALIGNMENT OF THE INSTRUMENT

The alignment of the breadboard mainly relies on manufacturing tolerances and mechanical measurements. The optical measurements (namely the measurement of the Line Spread Function (LSF)) are only used to characterize and align the focal plane of the telescope and of the complete instrument. In particular, there is neither individual alignment of the lenses inside the barrel with optical feedback, such as with a dedicated centering machine, nor iterative alignment process of the barrels on the optical bench with successive measurements of the instrument image quality.

All the lenses in the barrels are aligned with respect to the barrel axis by manufacturing. The barrels are interfaced with the optical bench by brackets that are machined and aligned to make the position and orientation of the barrel axis coincident with the optical axis that is defined on the bench. Consequently, the dimensional control of the brackets during manufacturing is a key step in the AIV sequence of the EBB, so as to have a good characterization of the optical axis with respect to the brackets.
Mechanical alignment means are nevertheless foreseen to align the bracket with respect to the optical axis with the 3D CMM. The degrees of alignment are limited to the position of the barrel axis and to its orientation around the axis that is perpendicular to the bench. The alignment is performed via shims that are located between reference surfaces located on the bracket and pins inserted in the optical bench. The minimum alignment step is defined by the shim resolution; typically shims can be adjusted to 5 µm. The alignment accuracy is rather related to the 3D CMM accuracy, i.e. 10 µm for the lengths involved in the FIMAS optical bench. This alignment method also allows for a good reproducibility of the alignment without additional 3D measurements.

The alignment of the slit first requires the characterization of the focal plane of the telescope. The focal plane position is measured with the 3D CMM. The slit is aligned such that its edges are coincident with the telescope focal plane position. The alignment of the slit takes advantages of the slit manufacturing process that allows to create measurement reference surfaces on the back surface of the slit, where the slit edges are defined. The slit support is therefore aligned with pins and shims techniques (as described in the above paragraph) and 3D CMM measurement. The slit is positioned along the optical axis to an accuracy that is better than 20 µm with this technique.

In order to fulfill the instrument spectral performances, the slit axis needs to be co-aligned to the grating axis. Here, the slit axis is kept fixed, while the grating orientation can be adjusted on the support. The alignment is performed with a theodolite. It is used to simultaneously characterize the slit edge orientation (direct look on the edge of the slit) and the grating line orientation (thanks to fiducial marks that are grooved on the grating substrate). The accuracy of the co-alignment is better than 100 µrad with this technique.

V. OPTICAL CHARACTERIZATION

The optical characterization of the integrated and aligned EBB involves the measurement of the Line Spread Function (LSF) of the telescope and of the complete instrument. The spatial resolution is measured with a knife-edge test setup. The knife-edge test consists in (see Fig. 4)

1. A collimated beam fed into the instrument (corresponding to a single angular direction within the FOV),
2. An edge at the focal plane of the instrument under test,
3. A CCD detector that is located ~ 10 mm behind the edge,
4. A scan of the edge along ACT or ALT direction -the plane created by the successive positions of the edges defines the current focal plane of the instrument -, and
5. A measurement of the complete intensity reaching the detector as a function of the edge.

The as-obtained 1D intensity profile is the knife-edge function (KEF, or edge spread function – ESF) of the instrument. It exhibits a sub-CCD pixel resolution provided the knife edge steps are sufficiently small. A step amplitude of 0.3 µm is considered. The derivative of the ESF yields the LSF along the edge scan direction. From the LSF, it is possible to characterize the RMS spot diameter along the scan direction. The RMS spot diameter is defined as

$$RMS\ Spot\ Diameter = 2\sqrt{\sum_i (X_i - X_{Center})^2 * LSF(X_i)}$$

where the LSF is assumed to be normalized to unity, i.e. $\sum_i LSF(x_i) = 1$, and the center of the LSF is given by $X_{Center} = \sum_i X_i * LSF(X_i)$.

The practical implementation of the knife-edge consists in a large slit (slit width > 2 mm) that is machined on a thin stainless steel substrate (~ 12 µm) with high precision techniques. Only one edge of the slit is used as the knife-edge. The knife-edge is supported on an Aluminum machined part on which the slit position can be measured with respect to mechanical reference surfaces. In particular, the knowledge of the position of the slit edge along the optical axis is of prime importance for the characterization of the focal plane position. The knife-edge support is mounted onto a remote-controlled linear translation stage. The translation stage can be mounted such that the scanning direction is horizontal or vertical and characterize the spatial resolution along one or the other direction. The error associated to the test set-up has been analysed and shows that it allows to extract the RMS spot diameter with an accuracy of 5.1 µm.

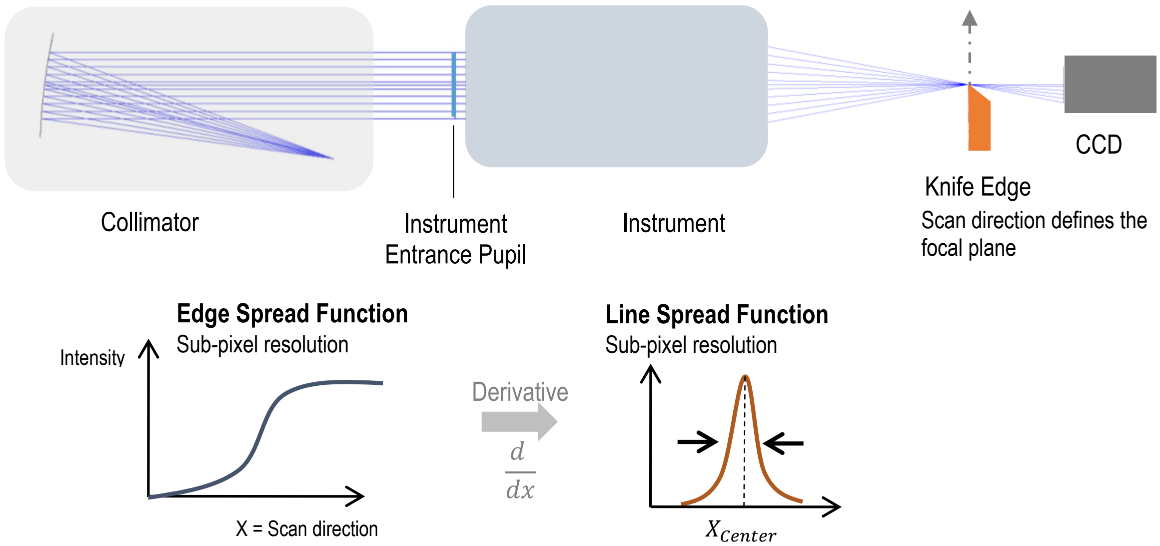

Fig. 4. Principle of the knife-edge test used for instrument spatial resolution measurement

The spatial resolution of the FIMAS instrument is measured in the following configurations:

1. The spatial resolution of the telescope is measured in the along-track direction, i.e. direction perpendicular to the edge of the FIMAS slit, and
2. The spatial resolution of the complete instrument is measured in the across-track direction, i.e. direction that is parallel to the edge of the FIMAS slit.

To this aim, the knife-edge assembly is mounted successively at the telescope focal plane and at the instrument focal plane. The knife-edge scan direction is adapted correspondingly to the direction of interest. The knife-edge is first positioned at the nominal telescope/instrument focal plane position with the help of the 3D CMM on reference surfaces. The measurement of the RMS spot diameter is then used to iteratively re-position the knife-edge along the optical axis direction.

The spatial resolution of the telescope in the along-track direction that is measured at the optimized focal plane position is shown in Fig. 5 – left panel, while the spatial resolution of the instrument in the across-track direction is shown in Fig. 5 – right panel. The corresponding RMS spot diameter are compared to the Monte-Carlo analysis predictions at 1-sigma confidence level in Table 2.

The measured spatial resolutions are consistent with the theoretical predictions, thus demonstrating the compliance of the opto-mechanical design to the required performances.

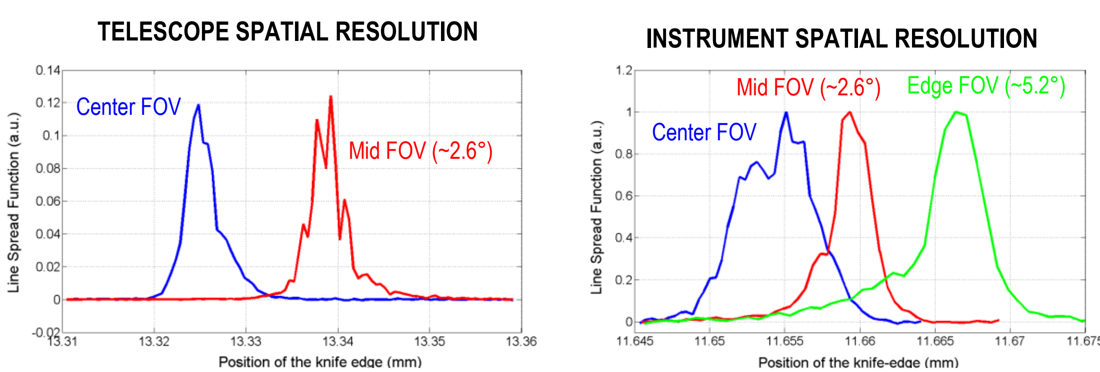

Fig. 5. Line Spread Function that is measured at the telescope focal plane in the along-track direction (left) and at the instrument focal plane in the across-track direction (right)

Table 2: RMS Spot diameter at telescope focal plane in the along-track direction and at instrument focal plane in the across-track direction

RMS spot diameter in along-track direction – at optimized position of telescope FP	**Center FOV**	**Mid FOV**	
Measurement	4.4 µm	2.9 µm	
Error	5.1 µm	5.1 µm	
TOTAL	**6.7 µm**	**5.9 µm**	
Monte-Carlo predictions at 1σ confidence level	**6.6 µm**		
RMS spot diameter in across-track direction – at optimized position of instrument FP	**Center FOV**	**Mid FOV**	**Edge FOV**
Measurement	4.9 µm	3.9 µm	6.9 µm
Error	5.1 µm	5.1 µm	5.1 µm
TOTAL	**7.1 µm**	**6.1 µm**	**8.6 µm**
Monte-Carlo predictions at 1σ confidence level	**12 µm**		

VI. CONCLUSION

The opto-mechanical design and associated optical performances of the FIMAS EBB are described and discussed in this paper. The opto-mechanical design of the instrument combines the needs for (1) tight positioning accuracies of the lenses and (2) a fast and reliable integration sequence. The success of the FIMAS EBB design relies on very good manufacturing capabilities associated to tight mechanical controls with 3D measurements.
The instrument reaches the required optical performances with the sole optical alignment of the telescope and instrument focal planes. The alignment of the other elements do not require any optical measurement and is guaranteed by a combination of manufacturing tolerances and mechanical measurements. This significantly reduces the alignment complexity and duration, and hence, favors a low contamination level on the optics at the end of the AIV campaign.
The presented design concepts constitute an interesting design basis for the next developments of the FLEX mission, as well as for other future space instruments.

VII. ACKNOWLEDGMENT

We thank the ESA FIMAS team for its constructive support throughout the project. We are also grateful to the FIMAS and FLEX teams from Airbus D&S for the successful collaboration.