ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

High precision assembling process and optomechanical characterization of the optical subassemblies for the ENMAP hyper spectral imager instrument

Annalena Altbauer

Markus Glier

Andreas Mezger

Stephanie Bogner

et al.

International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 1056224 · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296196

HIGH PRECISION ASSEMBLING PROCESS AND OPTO-MECHANICAL CHARACTERIZATION OF THE OPTICAL SUBASSEMBLIES FOR THE ENMAP HYPER SPECTRAL IMAGER INSTRUMENT

Annalena Altbauer[1], Markus Glier[1], Andreas Mezger[1], Stephanie Bogner[1], Markus Erhard[1], Manuela Sornig[2], Sebastian Fischer[2]

[1]OHB System AG, Manfred-Fuchs-Str. 1, D-82234 Wessling, Germany
[2]German Aerospace Center (DLR), Koenigswinterer Str. 522-524, D-53227 Bonn, Germany

I. INTRODUCTION

The Environmental Mapping and Analysis Program (EnMAP) is a German hyperspectral satellite mission that aims at monitoring and characterizing the Earth's environment. The so called Hyper Spectral Imager (HSI) comprises a Three Mirror Anastigmat (TMA) as telescope and two spectrometer (VNIR and SWIR) [3], [4]. The two spectrometer are based on a novel combination of an Offner and a Fery Prism design [4]. In total, telescope and spectrometer comprise 9 mirror- and 6 prism-assemblies. For the assembly of the bare optical elements into their mounts a high precision adhesive bonding technology was developed. The work presented within this paper describes this technology and shows how it is applied to the integration of in total 10 prism- and 15 mirror assemblies, including EMs, EQMs, and PFMs.

II. ASSEMBLIES OVERVIEW

A. Mirrors

The EnMAP mirrors have a diameter in-between 70 mm and 250 mm. They are all made from NiP coated aluminum. The mirrors are mounted to the optical bench structure with bipods made from titanium. The bipods are fixed to the mirror elements by adhesive bonding. Two different types of adhesive bonding interface between mirror and each bipod were used (see also Fig. 1):

- One set of mirrors has bolts to which the bipods are mounted with 4 gluing interfaces per bipod.
- The other set uses a bull joint like interface with only one flat surface per bipod for gluing.

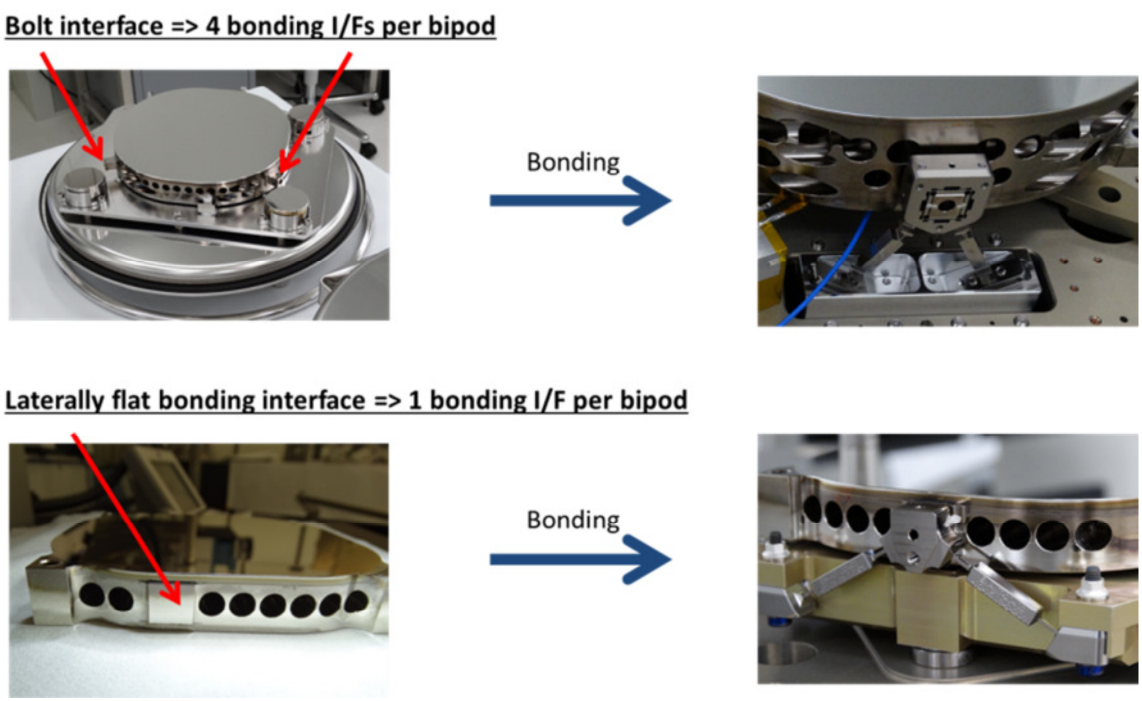

Fig. 1: 2 different types of mirror bonding interfaces

B. Prisms

The prisms made from Fused Silica and SF6 have dimensions between 160 mm and 190 mm in diameter, leading to high masses of up to 4 kg. A so called prism support frame is used to house the prism glass elements. Each prism is bonded to its support frame on 3 sides with a higher number of single bonding pads as shown in Fig. 2. In order to provide a good matching of the CTEs between mounting frame and glass element, Invar36 is selected for the frames of the Fused Silica prisms and Ti6Al4V for the SF6 prisms. The kinematic mounting elements between the prism support frames and the optical bench structure are either bipods (SF6 prisms) or so called universal joints (Fused Silica prisms).

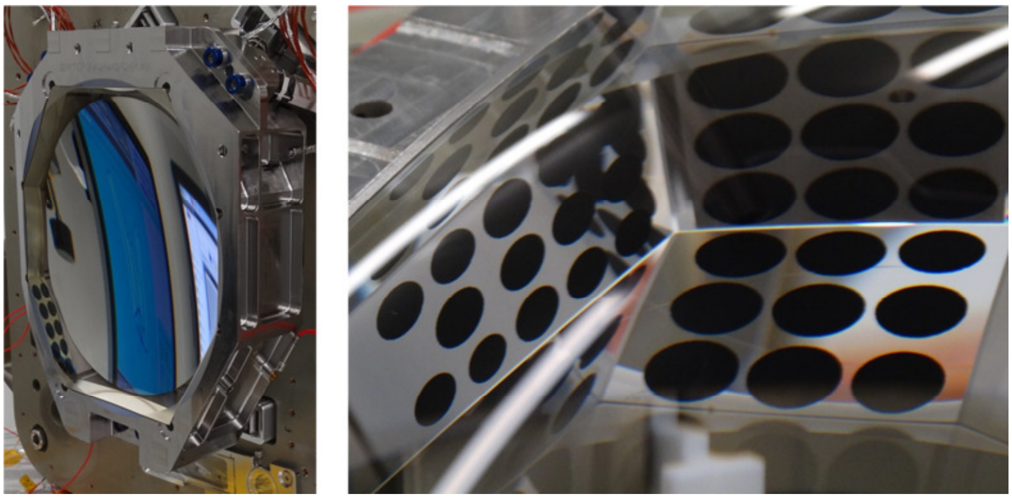

Fig. 2: prism bonding interfaces

C. Adhesive Joints

Beside others one of the reasons for the selection of adhesive bonding as mounting method is a compensation of the remaining coefficient of thermal expansion (CTE) mismatch between glass and metal frames. The requirements for the adhesive are derived from the high precision optics bonding application:

- High optical performance quality which requires stress-minimized bonding interfaces
- High structural loads incl. shock loads resulting in high required strength and shock resistance at the bonding interfaces
- Operational Temperature: 21°C
- Qualification Temperature Range: -30°C to +70°C
- High position stability

Shear and tensile tests were carried out with representative material samples in order to verify that the selected adhesive and materials fulfill the structural needs (results are given below in section V).

III. CLEANLINESS

The optical performance of the EnMAP instrument is sensitive to particular (PAC) and molecular (MOC) contamination of the optical elements. Particles on the optical surfaces would increase straylight. Molecular contamination might reduce the optical transmission or deteriorate the spectral behavior especially in the short wavelength range. From that, stringent AIT cleanliness requirements for the integration phase of the optical subassemblies of PAC ≤ 150ppm and MOC ≤ 200 ng/cm2 were derived.

In consequence the assembly and also the opto-mechanical characterization of the prism and mirror assemblies had to be performed under ISO5 cleanroom conditions, comprising all parts, materials and processes and also jigs and ground support equipment (GSE).

Furthermore especially the ground support equipment (GSE)development was challenging as there a limited availability of ISO5 compatible materials, equipment and instruments. The fulfillment of the requirements for MOC and PAC was monitored by special cleanliness witness samples, developed by OHB.

By all these measures the achieved cleanliness levels during integration and characterization of the optical subassemblies are PAC 2-11 ppm and MOC < 12.5ng/cm2.

As can be seen, all the processes, equipment and facilities of OHB lead to excellent cleanliness results for the optical subassemblies which over-fulfill the requirements by more than a factor of 10.

IV. PROCESS DETERMINATION AND QUALIFICATION

In order to reduce the risks and assure the success of the assembly of the flight hardware, a large qualification program was performed. Hereby, a manifold and complex combination of thermo-mechanical parameters, adhesive characteristics and different curing schemes, as well as sophisticated bonding interface geometries were covered.

A. Shear Tests

For the adhesive joints, shear stress is the most critical load and is therefore design driving. Shear tests were performed with representative material samples in order to verify the sufficiently good structural behavior of the adhesive joints. The sample material are based on the prism frame interfaces and mirror bipod interface with material combinations SF6 – Titanium, Fused Silica – Invar and Aluminium (Nickel-Phospor NiP coated Al) – Titanium (Ti). The sample design is optimized for bonding purposes and allows applying shear loads only by special gimbal mount interfaces.
The influence of different bonding gaps, different surface properties and treatments, thermal aging and thermal cycling loads to the ultimate shear strength were examined.

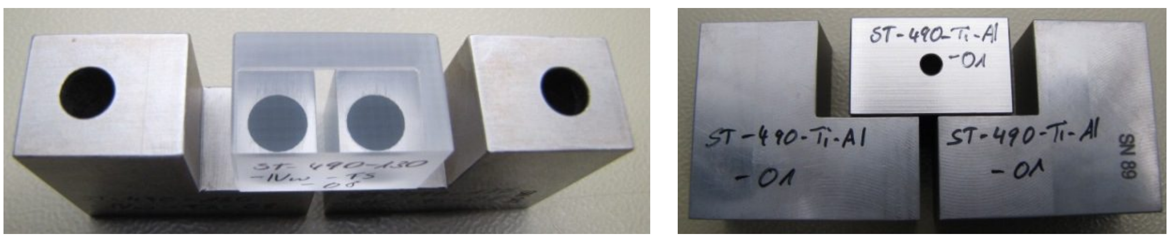

Fig. 3: Corresponding prisms with glass-Invar (left) and mirror with titanium-NiP Al alloy (right) samples

The adhesive was applied using insertion holes and suitable needles. During application, the adhesive pad diameter was monitored using a special developed realtime vision control software (see section VI.B.). As a next step, a specially developed thermal curing scheme was applied.

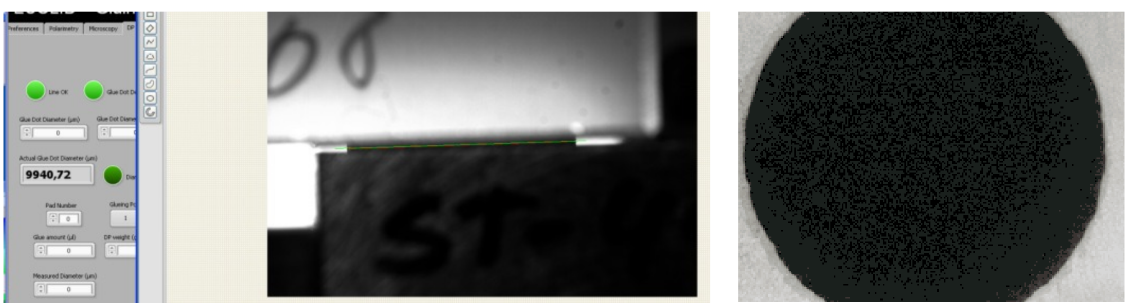

Fig. 4: Edge detection during bonding process and detailed close-up inspection of a bonding pad

The surface design, the adhesive and the curing methods results in a high reliable and constant ultimate shear strength of 25-30MPa under all test conditions.

B. Adhesive Characteristics and Curing Scheme

Shrinking of the adhesive during curing and its visco-eleastic properties can have a major impact on the Surface Form Error (SFE) of glued optical elements. Thus, the adhesive performance with respect to the gluing scheme was thoroughly investigated and optimized.
For the determination of the complex visco-elastic adhesive properties, several types of measurement were performed, by several analyses. Also the residual cure and the shrinkage of the adhesive was determined. As an example, the volume change of the adhesive over time and temperature measured by mercury-volume dilatometry is depicted in Fig. 5. For highly outgassing materials and curing additional a “Helium-Pycnometer” measurement (provides initial and final density) was performed.

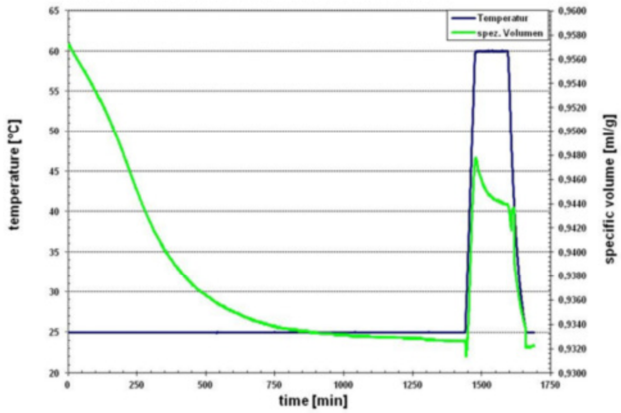

Fig. 5: Specific volume change and temperature profile over time during adhesive curing (measured by mercury-volume dilatometry

Additionally, to visualize the stress in glasses, induced by shrinkage, the strain in the bond-line was carried out with strain-scope (Fig. 9).

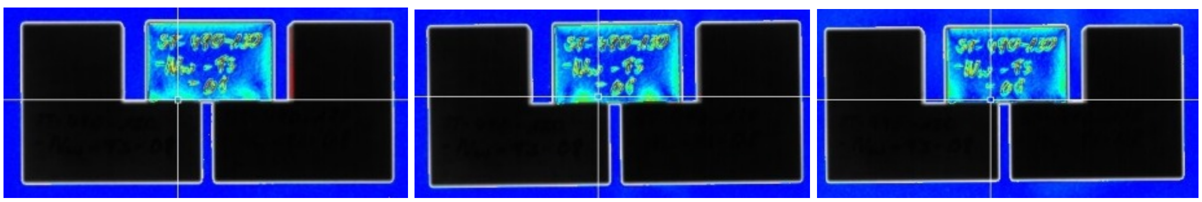

Fig. 6: Tension after room temperature curing (left), after heat treatment 1 (middle), after heat treatment 2 (right)

E. Outgassing

Epoxy adhesives are known as highly out gassing materials. In order to verify that it still meets the MOC requirements of this optical space application, outgassing tests were performed. The results show, that without further treatment, the outgassing values would be too high. For a minimization of the outgassing after assembly on system level, an appropriate out-baking procedure is needed to be applied already on sub-assembly level.

To ensure the required cleanliness and to remove outgassing contaminants during the elevated curing and out-baking process, the assemblies have been thermally treated in ultrapure nitrogen flushed compartments.

F. Structural- & Thermal and Optical Performance Test, Prediction and Model Correlation

The SFE of the optical surfaces is tested by an interferometer on a sophisticated test-set-up. The evaluation of the SFE data provided by the spectrometer is performed by a dedicated software, developed in house. For that purpose SFE data of several measurements need to be mathematically processed with each other, but also with simulated SFE data obtained by FEM analysis (e.g. the influence of the gravity effect). Thus, the validity the tested and simulated data needs to be verified by correlation of the FEM model with the test results.

Having a validated model, test set-up and data evaluation in hand, the influence of each integration process step, but also the impact of structural and thermal testing on the optical performance i.e. the SFE can be quantified.

Among others, dedicated qualification models (EQMs) of prism and mirror assemblies were subjected to structural tests, adhesive impact tests, stress annealing test, gravity tests, thermal cycling and thermal vacuum tests. The results were compare to the predicted value.

The gravity release displacement and the gravity induced SFE (called "gravity sag") is determined by measuring the optical performance and the relative position of the prism in different orientations. This test was used for the model correlation of the FEM model. The test prediction and the analyzed/predicted surface deformations (gravity load cases) correlate well with the measured data. Therefore the FEM model and analysis approach has been completely validated.

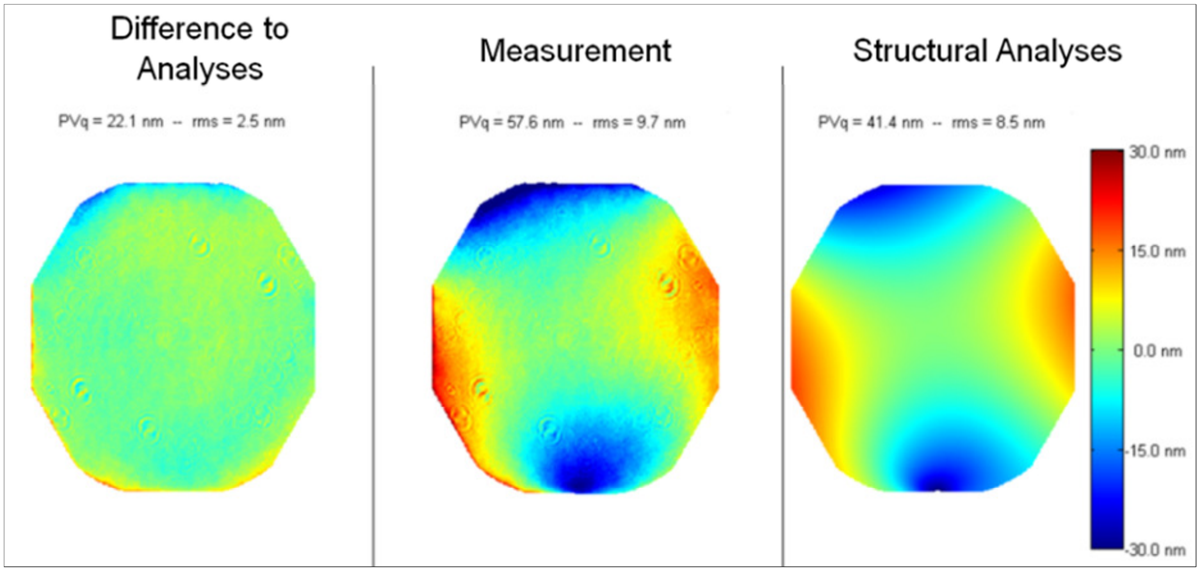

Fig. 7: Gravity induced SFE measurement and initial analysis results

The structural results of the vibration test, like the response of the acceleration sensors, performed notching, and assessment of the results wrt. requirements was successful. The optical performance after the vibration test was stable and remained unchanged within the measurement accuracy.

The performance stability of the assemblies were tested by subjecting them to different thermal loads. Thermal test leads ultimately to an ideal adapted process, which enables that the SFE stays stable within the required limits. The tested assemblies have survived the required loads without any damage.

V. BONDING IMPLEMENTATION

The bonding interface design requires a high precision alignment of the bonding gap and a good knowledge of the applied bonding area. Two types of control systems were developed. A camera based vision control system provides a real time observation of the adhesive injection process. In particular, the automated detection of the diameters of the bonding pad, the gap width and the element positions with micrometer accuracy. In addition a sample based process control was performed, to ensure the quality of the bonding and to proof a workmanship without any errors.

A. Alignment Methods

Special GSE for handling the heavy and sensitive optical parts was needed prior bonding and for later precise alignment of the gluing gap. Alignment / Bonding Gap stability had to be guaranteed by the GSE to 100% during bonding and curing. Achieved bonding and alignment accuracies were:

- Bonding gap / thickness: <10µm
- Bonding pad diameter : < 5% deviation (for indirect bonding)

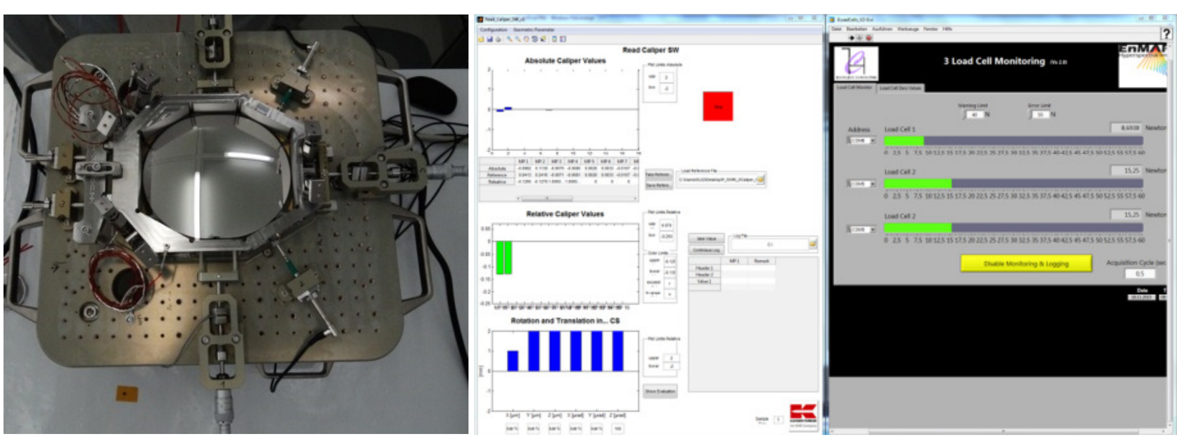

Fig. 8: Example of a prism alignment & bonding MGSE (left) and Alignment Software (right)

B. Realtime Vision Control Method

Three types of camera based vision control system were developed for the adhesive injection process. One for the laterally flat bonding interfaces, another one for the bolt bonding interfaces and thus providing four gluing interfaces per bipod and a special one for prism bonding using lot acceptance samples (LAS).

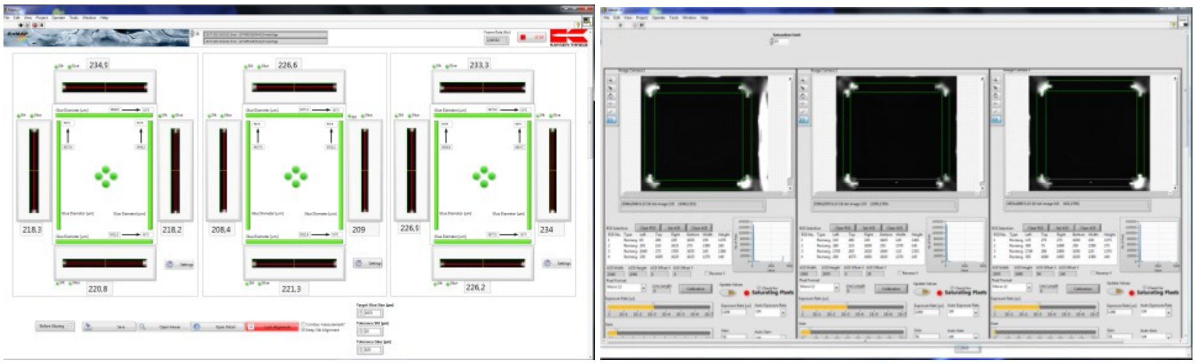

Fig. 9: Examples of the vision controlled bonding software

Similar to most machine vision applications, telecentric cameras were used to ensure a perspective-distortion-free image and orthographic view of the observed gaps. To detect and measure the edges of each gap and of the epoxy spot an analysation and control software was developed. For both types of interfaces a flat, diffuse background illumination was developed using electroluminescent foils or led with special acrylic light guides.

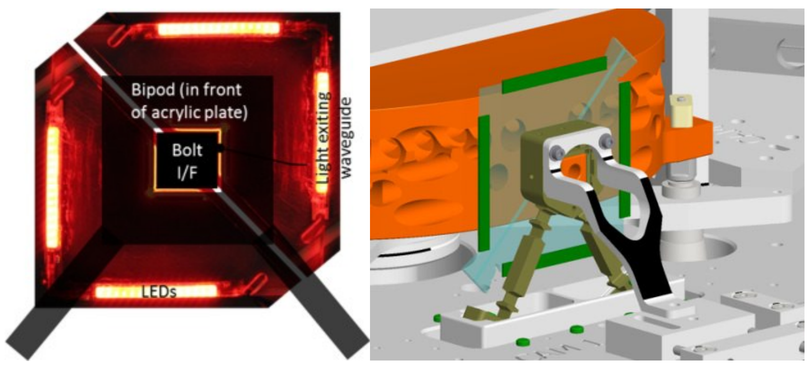

Fig. 10: Background illumination system for bolt type bonding interfaces

C. Sample Based Process Control

The gluing diameters at the prism assembly cannot be controlled and online monitored due to the prism's total internal reflection, apart from the design that they lie one above the other.

Therefore test and process qualification samples and a processed based vision control software for alignment and bonding was developed.

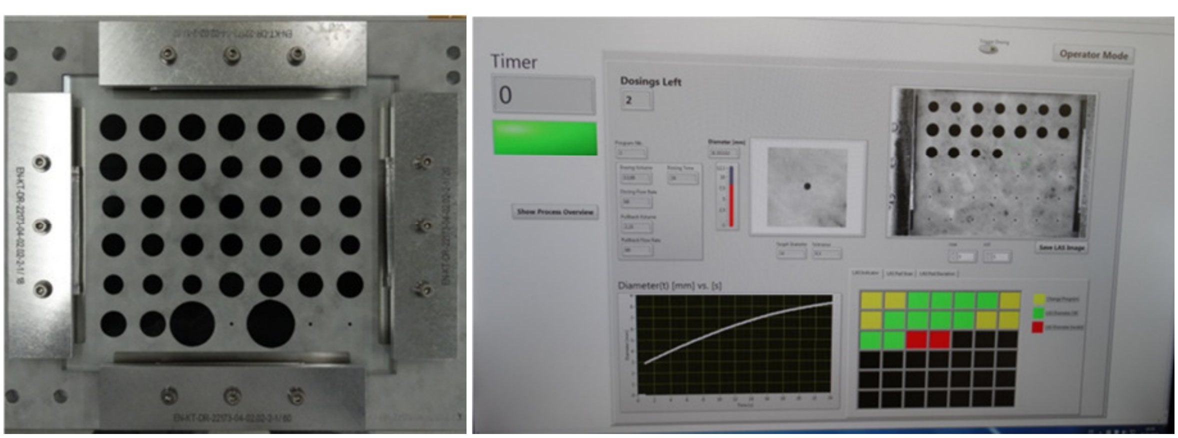

Fig. 11: Lot acceptance sample for achievement of gluing pad diameters

VI. PRECISION AND PERFORMANCE CHARACTERIZATION METHODS

A full optical and mechanical characterization of the assembled optical elements was performed, to enable the prediction of the optical instrument performance and to provide references for the following integration into the optical bench structure of the Instrument Optical Unit (IOU).

A. Mechanical Characterization

A precise 3D-CMM measurements have been carried out, in order to determine the relation between the as-built mechanical and optical coordinates of the assemblies with respect to their mounting interfaces. All generated data together with the optical characterisation data went into a data base to be used for the next step in the integration, the so called interface generation.

The interface generation concept is described in detail in a separate publication [1].

B. Optical Characterization

A fast Dynafiz 6'' Fizeau interferometer setup, mounted on a stiff, heavy duty and precise Hexapod and special developed MGSE has been used for the SFE measurement of all assemblies and elements. This setup allowed fast repeatable measurements under ISO5 cleanroom conditions. The set-up was validated to deliver reliable absolute SFE and post-processed relative SFE changes with an error of < 4 nm RMS for flat and any spherical surfaces.

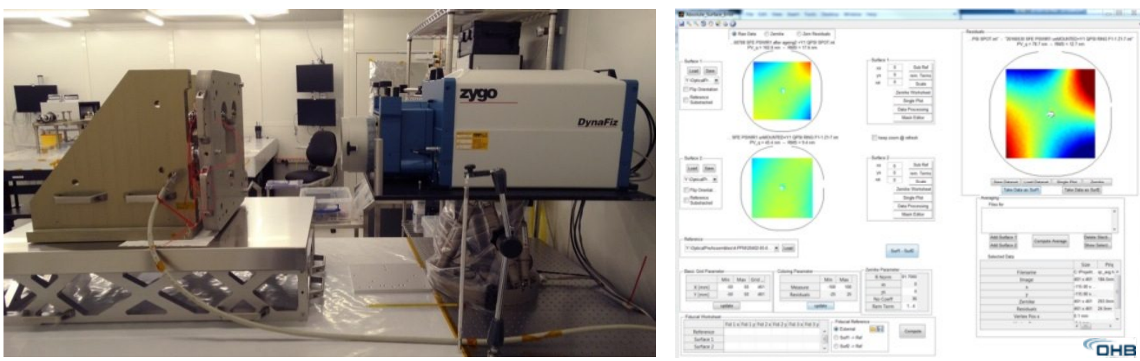

Fig. 12: SFE interferometric measurement setup (left) developed post processing software (right)

Due to the fact that no dedicated fiducial markers could be applied to the flight mirrors and prisms the "natural" in-situ fiducials like outer dimensions and SFE-"features" needed to be used instead for the post-processing and calculations. Furthermore gravity induced SFE and thermal SFE changes, calculated by FEM analyses had to be considered. Therefore instead of using the standard available interferometric evaluation software a sophisticated post-processing tool suite software based on Matlab has been developed allowing the calculate any absolute SFE or SFE changes from the exported measured interferometric data. The developed software is also able to read and evaluate FEM data as well as many other special optical parameter data (birefringence measurement, clear aperture polygons). Furthermore generic mathematical operations, coordinate transformations and special fiducial fitting and calculation algorithms have been implemented which were necessary for the required lateral precision of multiple surface data to calculated to each other.

As a result very precise post-processed SFE data values and plots referenced to a defined coordinate reference frames with a high lateral accuracy < ±0.5mm could be provided. Each of the calculated SFE data could be corrected for temperature changes, gravity loads and transmission sphere/flat errors and superimposed with intermediate measurement in order to provide relative changes as well.

VII. CONCLUSION

A high precision bonding- and monitoring process for large and heavy prisms and metal mirrors was developed and validated successfully within the EnMAP program. All 10 EnMAP prism- and 15 mirror assemblies, including EMs, EQMs, and PFMs are integrated and tested and meet the requirements.

The developed processes are ready to be applied to future applications other projects like EUCLID [2] or FLEX.

For any high performance optical application which uses adhesively bonded optical elements, the proper selection of the adhesive and an adaptation of the curing process to the respective design and environmental conditions is essential. Finally, the selected adhesives and the specially developed bonding- and curing procedure could achieve:

- the desired strength of the bonding interfaces
- good visco-eleastic properties of the adhesive
- low and reduced outgassing values
- minimized stress at the bonding interfaces
- good reproducibility of the process
- high reliable bonding joints

High precision SFE testing and CMM characterisation with dedicated set-ups and special developed data evaluation software is a key for development, monitoring and verification of high precision bonding and integration processes with low impact on the SFE.

Dedicated GSE is required for precise handling and alignment of the optical components to their mounts, as well as for online monitoring the gluing process and the gluing gap. Time and effort for GSE development should not be underestimated.

Very good cleanliness and contamination results can be achieved by putting a high effort to:

- Cleaning of parts (GSE and flight hardware)
- Parts-, Material and Process selection, validation, verification and monitoring
- ISO5 compatible GSE
- Training of staff

ACKNOWLEGDEMENTS

The work presented in this paper was performed on behalf of the German Space Agency DLR with funds of the German Federal Ministry of Economic Affairs and Technology under the grant No. 50 EP 0801. The authors are responsible for the contents of this publication.

REFERENCES

[1] J. Kolmeder et al, “Optical Integration Process for the Earth observing satellite mission EnMAP”, ICSO 2016, unpublished

[2] C. Gal et al, “Development and verification of high precision cryogenic lens holders”, Conference Proceedings ICSO, 2014

[3] S. Fischer et al, “The hyperspectral instrument onboard EnMAP, overview and current status”, ICSO 2016, unpublished

[4] B. Sang et al, "The EnMAP hyperspectral imaging spectrometer: instrument concept, calibration, and technologies", Proc. SPIE 7086, Imaging Spectrometry XIII, 708605 (August 27, 2008); doi:10.1117/12.794870