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OPTICAL INTEGRATION PROCESS FOR THE EARTH-OBSERVING SATELLITE MISSION ENMAP

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I. INTRODUCTION

The Environmental Mapping and Analysis Program (EnMAP) is a German hyperspectral mission with pushbroom type imaging spectrometers covering the wavelength ranges from 420 nm to 2450 nm. The ground sampling distance is 30 m with a total swath of 30 km, while the spectral sampling distance is roughly 5 nm to 12 nm. The optical layout of the instrument can be seen in Fig. 1. Further information about the hyperspectral instrument is given in [1].

Design, assembly and alignment of the EnMAP hyperspectral instrument are mainly driven by the stringent MTF, keystone and smile distortion requirements, but also by a tight schedule. Thus, a two staged integration and alignment concept was chosen for the optics. The first step is a precise and highly predictable mechanical placement, which needs to be in the range of 50 µm in translation and 80 arcsec in rotation for the single optical elements. Only then the second step, the optically guided fine alignment of the corresponding subsystem can be performed, because it is limited by the maximum travel range of the compensator degrees of freedom.

This paper describes large parts of the first step, the so called interface (IF) generation. The IF generation uses numerous measurements in order to compensate manufacturing tolerances and calculates the IF elements - often complex 3D-shims - , which are necessary for the accurate mechanical placement of optical elements into the respective housing structure.

First, a general overview of the IF generation process is given, after which the single inputs and outputs are described in more detail. An example from the IF generation of the demonstrator telescope demonstrates the capabilities of this process.

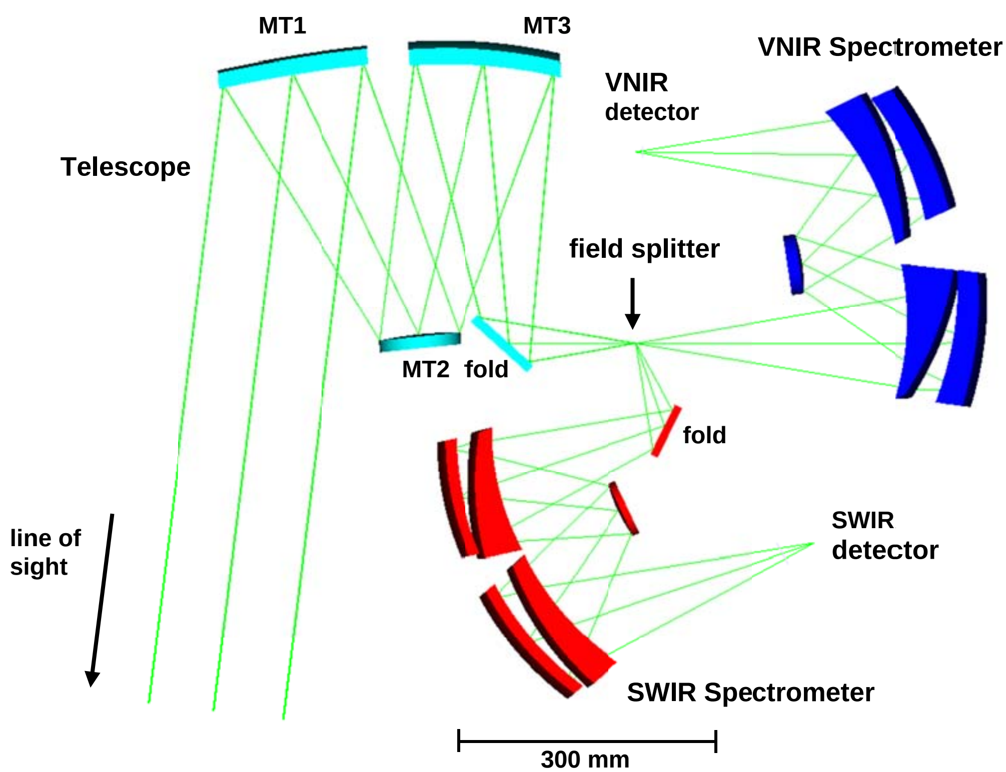

Fig. 1 A sketch of the three optical subsystems: telescope, VNIR spectrometer and SWIR spectrometer

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II. SIMPLIFIED INTERFACE GENERATION PRINCIPLE

The task of the IF generation is to provide correct positioning of the optical elements taking into account various manufacturing tolerances. Fig. 2 shows simplified sketches in order to demonstrate the different phases of the IF generation. Subplot a) shows the design status of a fictional two mirror system with bipod-mounted mirrors, a housing structure and four interface elements, shown in blue, which are located between the structure and the mirrors. In reality, however, there are deviations from the designed system. The actual surface forms of each mirror have some differences to the ideal surface forms (see b)). With the knowledge of the real surface forms, e.g. from interferometric measurements of each mirror, the system's optical performance can be adjusted via small movements of the mirrors as shown in c). Moreover, the interfaces of the bipods towards the IF elements have to be measured w.r.t. the corresponding mirror surface. But not only the mirrors, also the housing deviates from the design status as can be seen in subplot d). A dedicated measurement of the housing structure gives knowledge about the actual geometry. Consequently, the original (blue) IF elements do not fit to the actual mirrors and housing structure any more. However, by combining all the measurements, new (red) shims can be calculated, which position the mirrors at the desired location within the given housing (see e)).

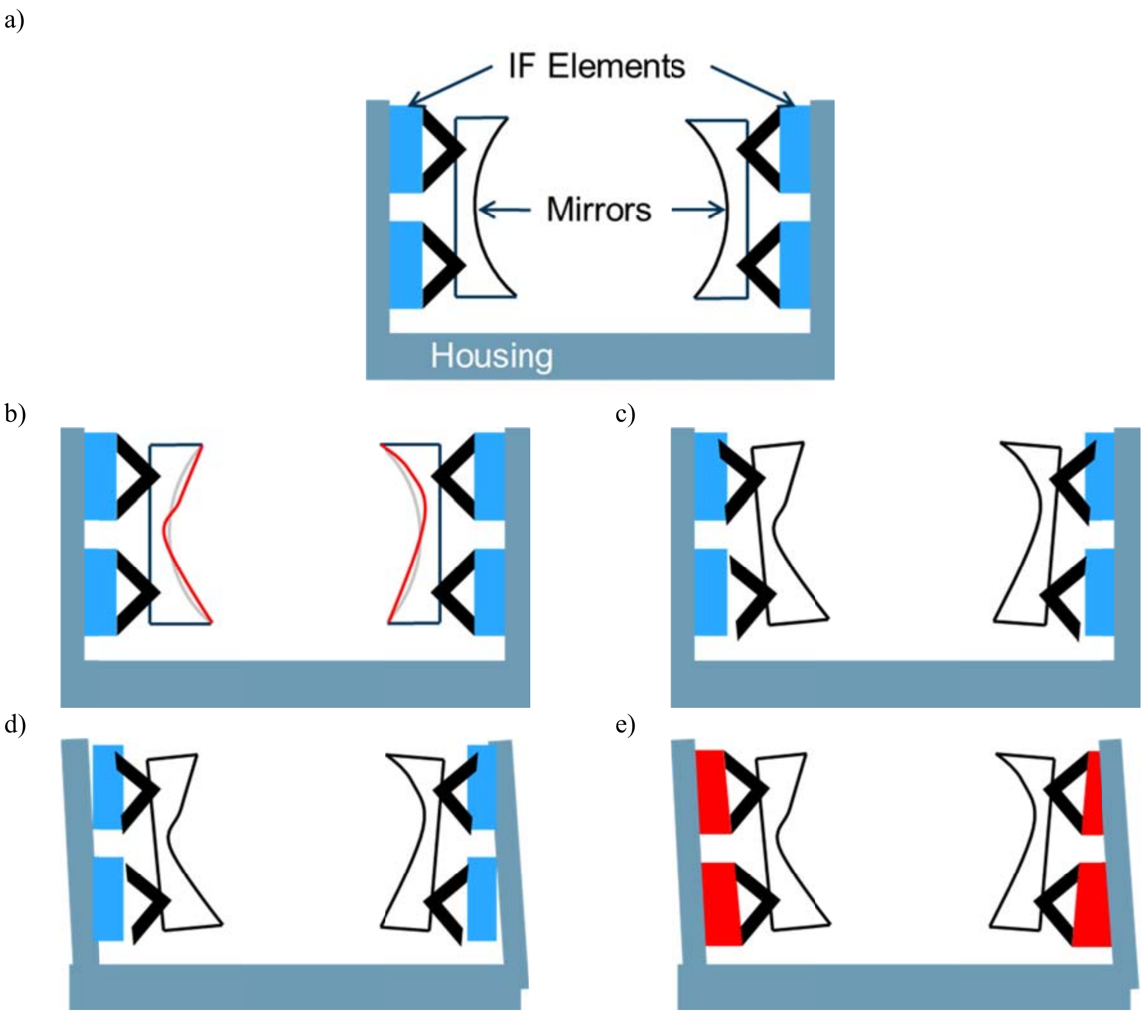

Fig. 2 A simplified sketch of the IF generation process. The design status is shown in a). Subplot b) depicts the actual surface form of the mirrors, which are compensated by adjusting the mirror positions (c). The as-built status of the housing is updated in d). The red IF elements of e) are the result of the IF generation process and place the mirrors at the intended position

III. THE INTERFACE GENERATION PROCESS IN DETAIL

For the EnMAP hyperspectral instrument, the IF generation process is not as simple as show in the previous chapter. The process was already performed for the risk mitigation telescope (RMT), a demonstrator model of the flight telescope, and the flight telescope itself with each telescope having four mirrors and each mirror having three interface elements. IF generation for the VNIR spectrometer (incl. five optical elements) was recently finished at the time of writing and shims are currently manufactured. Furthermore, the IF generation still needs to be performed for the SWIR spectrometer (six optical elements), three cameras, the spectrometer slit assembly, the telescope-to-spectrometer alignment and two mechanisms. Each time, several measurements are involved and need to be processed. Thus, it is necessary to have a strictly organized approach for the IF generation.

For this reason, a dedicated software, called CS Engine, was developed. CS stands for coordinate system. The CS Engine is written in MATLAB and it essentially administers the coordinate systems (hence the name), the measurement features and the transformations between them. It also uses the .NET assembly interface to communicate with the commercial software SpatialAnalyzer (SA), which has many useful abilities, e.g. processing measurements, CAD exports, graphical visualization and data analysis.

Despite being the central part, the CS Engine is not the sole contributor to the IF generation process. Many other important tasks need to be done in the preparation and execution of the IF generation process. Laying the groundwork is on the one hand extensive and time-consuming, but on the other hand saves time for recurring activities and is mandatory for managing hundreds of coordinate systems and features along with numerous coordinate and interferometric measurements.

The IF generation workflow is shown in Fig. 3 and the single parts are explained in more detail in the following subsections.

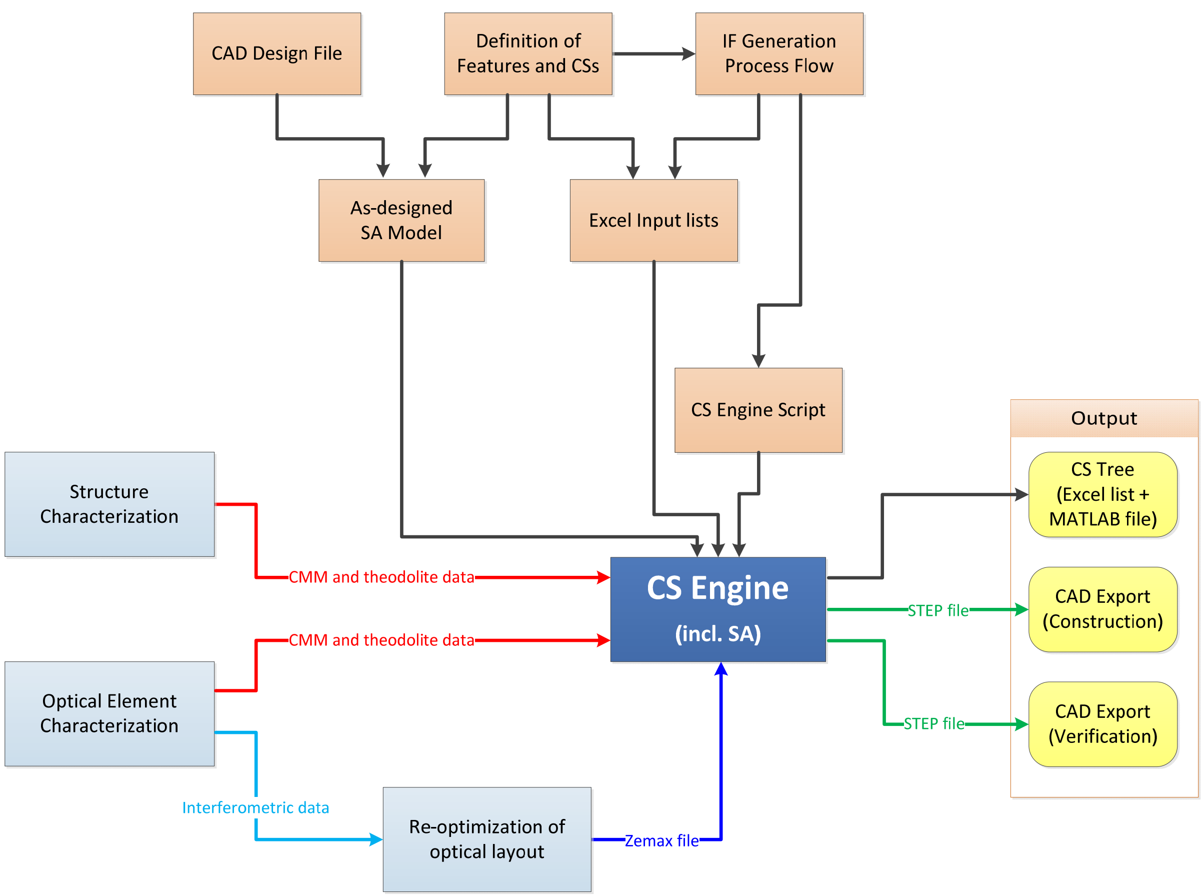

Fig. 3 The different inputs and outputs for the CS Engine during the IF generation process

A. Definition of Features and Coordinate Systems

The representation of the geometry of the structure and the optical elements is done via coordinate systems and measurement features. There are currently three types of features: the plane feature, the borehole feature and the sphere feature. The plane feature is defined by a small flat area and is represented by a plane in the CS Engine. The borehole feature is defined by a cylindrical hole drilled into a flat surface. The cylinder defines an axis, which is intersected with the plane of the flat area in order to obtain a single point. The sphere feature is given via a central point and a radius.

The features are also used to construct coordinate frames. There are several different methods to create a frame from features, e.g. via three planes or via a plane, a line and a point.

The definition of the features and coordinate systems is done in dedicated documents for the different subsystems. Each feature is marked in figures with an individual identifier and the construction method for the corresponding frame, which also has an individual identifier, is written down in the document. The document for the spectrometer housing structure e.g. defines more than 200 features and more than 40 coordinate systems.

B. IF Generation Process Flow

The IF generation process flow gives a hierarchical structure of the coordinate systems, the so called CS tree. Each coordinate system (except the master CS) is linked to a parent system with a transformation. It also contains crosslinks between frames that describe, which kind of information (e.g. from measurements or logical connections between coordinate systems) is applied to the CS tree in which order (see Fig. 4).

The IF generation process flow and the definition of features and coordinate systems are the two documents that lay the theoretical background for the IF generation process. All other tasks are based on these documents.

C. CAD Design File / As-designed SpatialAnalyzer Model

The CAD design file is used to establish a quantitative model of the design geometry for the housing and optical elements that are subject to the IF generation. The CAD file is imported into SpatialAnalyzer, where the features and coordinate frames can be defined according to the document described in subsection II.A.

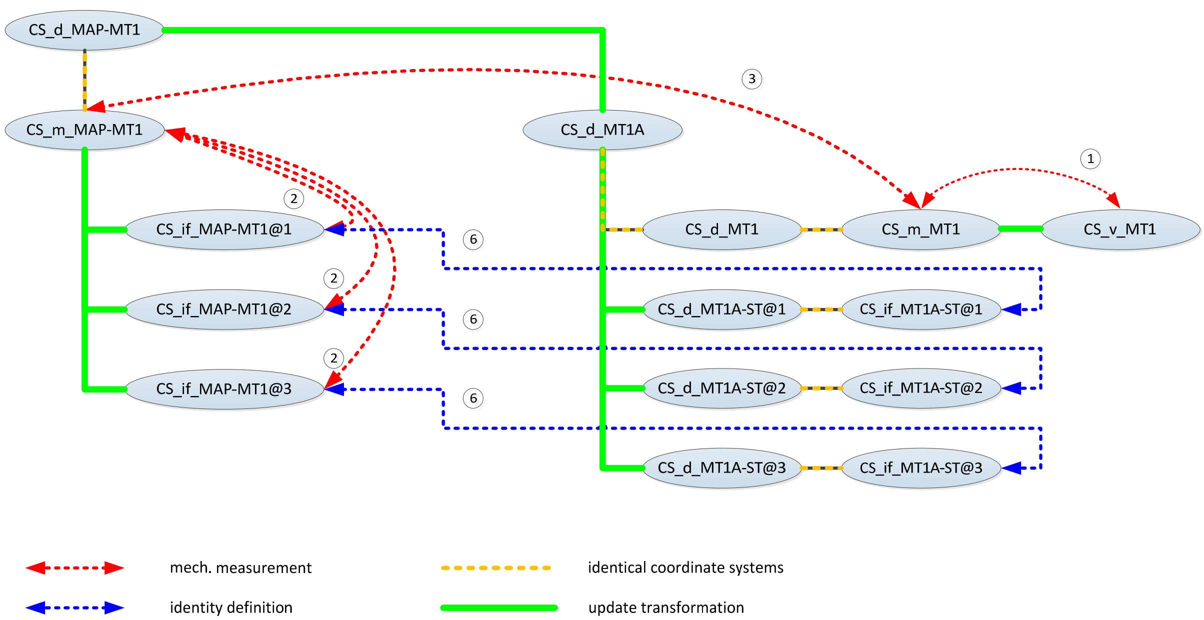

Fig. 4 The excerpt of the IF generation flow for the telescope primary mirror (MT1) shows the hierarchical structure of the coordinate systems. The red and blue arrows indicate information from measurements and logical connections, which is used to update the CS tree from the design status to the as-built status in the order of the labelling numbers. Updated transformations are shown in green.

The strength of the as-designed SA file lies in revealing errors and assessing the quality of measurements by comparing the measured geometries to the design. Deviations that are larger than the allowed tolerances indicate an error.

D. Structure Characterization

Measurements of the housing structures, more precisely the features of the housing structures, are done with a 3D coordinate measurement machine (CMM) achieving accuracies of better than 5 µm. The measurement data is stored in a text file where each measured point is listed with its corresponding identifier and coordinate values. This high level of detail allows automation in processing the measurements as well as error detection as the points can be overlaid onto the design CAD and runaway values can be explained more easily.

In some cases theodolite measurements are also performed to give detailed angular information about the structure.

E. Optical Element Characterization

Characterization of the optical elements is done in a similar manner to the housing structure characterization. Each optical element is measured with a CMM and the data points are stored again in a text file.

Additionally, the surface form of each optical element is characterized via an interferometric measurement. This is necessary in order to know the actual surface shape of each optical element, which is later used in the re-optimization of the optical design.

Detailed information about the assembling process and characterization of the optical elements can be found in [2].

F. Re-optimization of the Optical Layout

The sag values from the interferometric measurements described in subsection E are converted to Zernike terms and entered into the optical design software Zemax. In order to achieve the best possible imaging performance with the as-built optical surfaces, an optimization of the layout is performed with several optical elements being allowed to vary slightly in their positions within a range of roughly ±1mm in translation and ±0.5° in rotation. The resulting Zemax file contains the positions of the optical surfaces with respect to each other and serves as further input for the CS Engine.

G. CS Engine Script and Excel Input List

The CS Engine is controlled via a script, which contains the file paths to the excel input list and the as-designed SA file. It also initializes the CS Engine and tells it to automatically process the excel input list. The excel input list enumerates the features and coordinate systems that either have to be read from the as-designed SA file or have to be constructed from the measurements. The excel list also contains the information of the parents to each coordinate system. This enables the CS Engine to build the CS tree with the transformation according to the design status. At the end of the automatic processing, the all measured features and the derived frames have been generated in SpatialAnalyzer and all as-designed and measured features and frames from SA have been read into the CS Engine.

From this point on, the script contains the orders for the different steps of the IF generation process that were defined in the IF generation process flow. Furthermore, the output is defined in the script.

H. Output

There are several possible outputs for the IF generation process. First, there is the SA file containing the features and coordinate frames giving the design status and the updated status, which shall be realized in the hardware, in parallel.

Second, the state of the CS Engine at the end of the IF generation process is stored, i.e. the CS tree with its transformations between the coordinate systems and the transformations of the features. Further, an excel spreadsheet can be generated, which contains the CS tree for both, the design status and the updated status, in table format.

Another option is a CAD export, e.g. a STEP file. The features, which shall be exported are defined in the IF generation script and written to SA. Then the SA built-in CAD export function is used to create the file. In EnMAP, a CAD file for each calculated IF element is created and passed on to the engineering department, which generates drawings and files for manufacturing the IF elements.

Moreover, a CAD file containing the features of the housing and the optical elements in the expected position after integration of the optics is generated. This file is compared to CMM arm measurements once the integration is finished and the success of the placement can be evaluated.

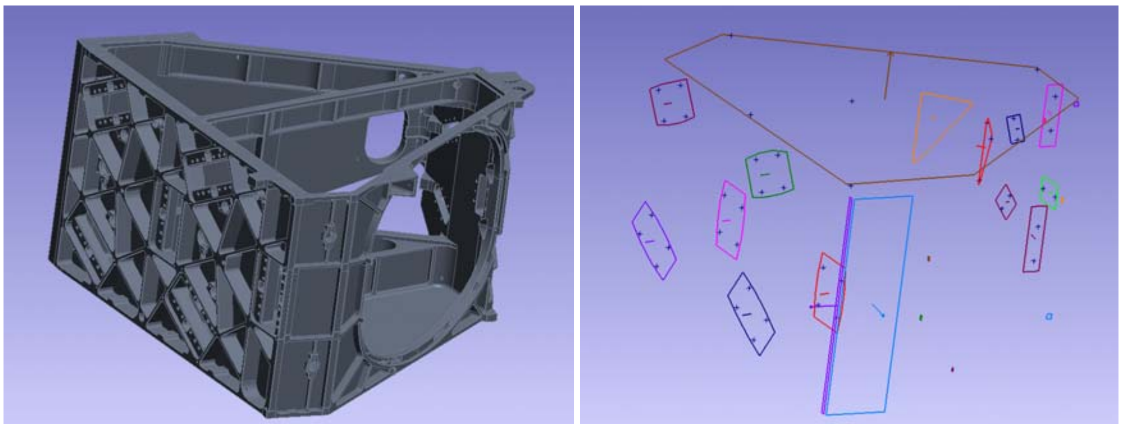

Fig. 5 The housing structure of the primary telescope. On the left is the CAD image, on the right is the representation in the CS Engine with plane and borehole features.

III. THE TELESCOPE IF GENERATION

The IF generation has been carried out already twice for the telescope, once for the demonstrator model and once for the flight telescope. Results from these processes are given in this section.

A. IF Generation for the Demonstrator Model Telescope

The main purpose of the demonstrator model telescope was to train the hardware AIT activities. But an important part was also the testing of the IF generation process, starting from the definition of the features and coordinate systems, the communication of these to the measurement personnel and the measurements themselves. Furthermore the CS Engine code was debugged during these activities. The IF generation was performed, the 3D shims were manufactured according to the data from the IF generation and the mirrors were integrated using these shims. So the complete process chain has been tested within the frame of the demonstrator model telescope.

394 features and 99 coordinate systems were defined in order to represent the geometry of the housing structure and the four mirrors including mounts and IF elements. In total, the IF generation was performed without any major difficulties.

The secondary mirror was initially misplaced as a single shim at one of the bipod legs accidentally dropped from its pocket. The error was quickly discovered after CMM arm measurements and an inspection of the telescope and the shim was inserted correctly.

Table 1 shows the final differences between the measured positions and the expected positions according to the IF generation for the four mirrors of the demonstrator telescope. All values are within the required values, except MT4 rotation about the y-axis. Nevertheless, this deviation is still acceptable as MT4 is only a fold mirror.

This result proved that the IF generation process along with the CS Engine as well as the manufacturing and integration of the interface elements are working very well.

Table 1 Differences between measured positions and expected positions after IF generation of the mirrors for the demonstrator telescope are given in the columns labelled "meas.". The required accuracy can be seen in the columns labelled "req."

	MT1		MT2		MT3		MT4	
	meas.	req.	meas.	req.	meas.	req.	meas.	req.
Δx [µm]	-2	60	-5	60	-15	60	-	-
Δy [µm]	8	60	44	60	-22	60	-	-
Δz [µm]	-11	60	-53	60	-8	60	17	58
ΔRx [arcsec]	35	100	14	122	24	100	-11	110
ΔRy [arcsec]	-16	100	51	122	-11	100	-133	110
ΔRz [arcsec]	-20	134	-70	140	-25	134	-	-

B. Flight Model Telescope

Being performed after the successful integration of the demonstrator model telescope and having benefited from this experience, the IF generation and manufacturing of the IF elements of the flight model telescope went without complications as it was mainly a repetition of the tasks with the new measurement data of the flight model.

However, after integration of the optical elements into the housing, the verification measurements with the CMM arm suggested a misplacement of the mirrors of up to 200 µm for some degrees of freedom. Repeated measurements with the CMM arm brought varying results and indicated rather a problem with the CMM arm than with the placement accuracy. The source for the inaccurate measurements was later identified to be the mount of the CMM arm. Due to schedule reasons, fine alignment was started without waiting for the newly manufactured mount as an assessment predicted the fine alignment not to be restricted by these misplacements. As downside, this made new measurements with the improved CMM arm impossible and it is still unknown, if there was really a misplacement or if the measured violations of the requirements just came from the instable CMM arm mount.

In the end, the flight telescope was successfully aligned and characterized.

IV. CONCLUSION

We have developed a highly structured and systematic approach for the mechanical integration of optical or other elements into a housing structure. This method is based on a dedicated software called CS Engine, which combines many measurements in order to calculate the IF elements, which put the optical elements at the desired position. The CS Engine is very powerful in identifying measurement errors by comparing the measurements to the design status. Revealed errors are quickly corrected due to scripting of the CS Engine commands, which provides a high traceability of the performed actions. Moreover, the CAD export offers a safe interface to the engineering department for generating the drawings and files for manufacturing. Another advantage is that at the end of the IF generation we obtain an accurate model of the as-built status of the optical instrument including all relevant information on positions and interface locations of optical elements.

The whole IF generation process including preparation (i.e. establishing the documents), measurements, processing of the measurements, calculation of the IF elements, manufacturing of the often complex 3D shims and integration of the optical elements was successfully performed for the demonstrator and flight model telescopes.

IF generation for the VNIR spectrometer has been finished and the IF elements are currently being manufactured. All interferometer and CMM measurements for the SWIR spectrometer are finished as well and IF generation with the CS Engine will commence next.

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