

Integration of a hyperspectral optical filter onto a detector

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ABSTRACT

The compact RAINBOW optical payload is a hyperspectral instrument based on filter-on-chip technology and optimised for agricultural applications. To access the huge smart farming market, a spatial resolution of 20m or better, and bands in the spectrum from 0.4 to 1.7 μm are required. In the de-risking activity, (co-)funded by European Space Agency (ESA), the filter-on-chip technology was breadboarded, leading to a cost-efficient design suitable for small satellites, and supporting a business case focusing on smart farming. [1] The de-risking project was performed under the lead of Airbus Defence and Space GmbH - Earth Observation, Science and Exploration.

The Rainbow instrument concept includes a telescope and a detection chain of which the detector is equipped with three structured, linear variable bandpass filter (LVBF) on one substrate. The filters are developed and manufactured by Fraunhofer Institute for Surface Engineering and Thin Films (IST) [2]. The hyperspectral bands generated by the Filter enable the detection of agricultural and biochemical data by the Rainbow instrument.

The aim of the activities was to integrate the coated filter substrate onto the detector surface. The filter bands have to be aligned to the detector pixel rows with an accuracy of less than 4 μm .

Different options of filter to detector integration were developed. Some options use mechanical interfaces of the detector carrier for mounting the filter. Options for direct mounting were developed too. A trade off process was performed to identify the best suitable solution. The integration options and the trade-off will be described in the paper.

Keywords: Filter on detector integration, alignment, linear variable bandpass filter, hyperspectral instrument

1. INTRODUCTION

The development of a cost-effective integration process of hyperspectral filters onto detectors was the aim of the Rainbow de-risking project. Based on the development of filters and the definition of the instrument, including the choosing of a detector, different integration concepts were developed. After a trade-off, a favorite integration concept was realized and characterized. After the development and testing activities, a process for filter to detector integration is available for the realization of detector units for several hyperspectral instruments.

2. RAINBOW MISSION DESCRIPTION

The compact RAINBOW optical payload is a hyperspectral instrument based on filter-on-chip technology and optimised for agricultural applications. [1]

Current multispectral data are a solid input data source for agricultural services, but they cannot capture the individual spectral absorption bands that characterize the plant biochemical parameters. Those are necessary to go from crop observation to a deep understanding of the causes of what is happening in the fields, and from qualitative description to quantitative assessment, as a baseline for precision farming on a parcel level.

To be able to address the commercial needs – for accessing the huge smart farming market, for instance – a spatial resolution of 20m or better, and bands in the spectral range of 0.4 to 1.7 μm are required. Such operational, hyperspectral remote sensing data serving the requirements of enhanced agricultural Earth observation (EO) products are currently not available. A major challenge is the typical budget (volume, mass and resulting cost) of a traditional hyperspectral instrument (such as EnMAP or CHIME), leading to satellite costs that are not compliant with a reasonable commercial business plan. A filter-on-chip-based hyperspectral instrument optimized for agricultural applications is expected to solve the issue. RAINBOW is based on a cost-efficient design of the compact optical payload onboard a LEO small satellite supported by appropriate data fusion and processing.

In the de-risking activity, (co-)funded by European Space Agency (ESA), the filter-on-chip technology was prototyped, leading to a cost-efficient design suitable for small satellites, and supporting a business case focusing on smart farming. [1] The de-risking project was performed under the lead of Airbus Defence and Space GmbH - Earth Observation, Science and Exploration.



Figure 1: earth observation for smart farming (KI generated image)

3. RAINBOW BUSINESS CASE DESCRIPTION

The core business case for RAINBOW lies in making hyperspectral agricultural intelligence economically accessible for operational services. The goal is to both enhance existing commercial services in smart farming, sustainable agriculture, carbon farming and food-security monitoring with hyperspectral information and develop completely new agricultural services that cannot be served with current multispectral data.

Thus, the RAINBOW mission concept targets a clear commercial gap in Earth Observation: today's freely available multispectral satellite data are useful for operational crop monitoring, but they do not provide the spectral detail required to quantify key plant biochemical parameters such as nutrient status, water content, stress factors or crop quality at the accuracy level needed for high-value agricultural use cases.

At the same time, traditional hyperspectral missions are typically too large, complex and costly to support a scalable commercial smart-farming business case. RAINBOW addresses this gap by developing a compact, cost-efficient hyperspectral payload based on filter-on-chip technology, optimised specifically for agricultural applications. The instrument is designed to cover more than 30 spectral bands in the 440–1700 nm range and to achieve a spatial resolution of 20 m or better, which is considered necessary for parcel-level agricultural services (see figure below).

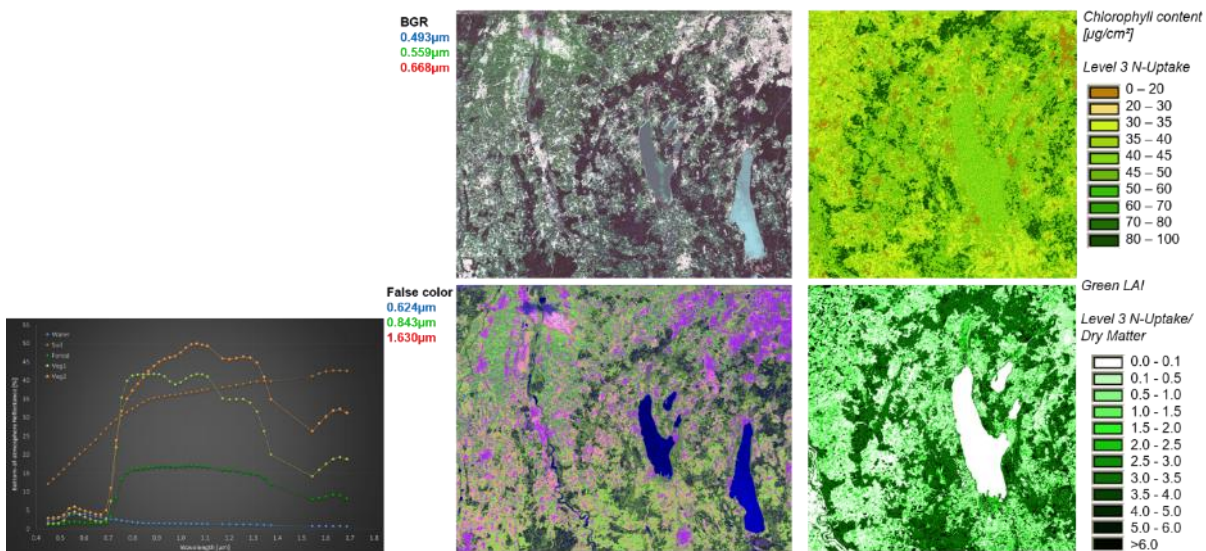


Figure 2: Simulated spectra and image with Rainbow specifications as demo dataset, Simulated Level 3 demo products, Alpine foreland Germany, 6th of July, Spatial resolution: 13/20 m, 48 x 60 km

The business case is built around not just selling these high-quality hyperspectral data but turning them into actionable insights. For farmers, extension services and agricultural industry, RAINBOW data can support more precise crop analyses, nutrient and stress diagnostics, irrigation and fertilisation decisions, yield forecasting and yield quality assessments, including indicators such as protein or nutrient content. This creates value through improved input efficiency, reduced costs, better resource management and more sustainable production.

The mission therefore has revenue potential not only as a data source, but as an enabler of higher-value analytics, subscription-based agricultural decision support, carbon certification support and commodity intelligence products.

4. RAINBOW INSTRUMENT CONCEPT DESCRIPTION

The Rainbow instrument concept is based on a filter-on chip spectrometer. This approach allows to omit dispersive elements, camera and collimation optics. The concept thus employs similar components as an imager, consisting of telescope and focal-plane assembly (FPA) only. In order to avoid chromatic aberrations, over the large spectral range from 440nm to 1700nm, the telescope is implemented as a reflective optical Ritchey-Chretien telescope which is consisting of two opposing mirrors.

Inner baffles block direct earth light paths entering the instrument around M2 and reaching the detector without being reflected by neither M1 nor M2. A short external baffle is foreseen in addition.

The instrument consists of an optical module and a Front-End electronics (FEE) unit.

The optical module collects the light from the Earth which then illuminates the detector where the photons are transformed into electrons. A spectral filter is mounted directly in front of the detector and performs the spectral filtering of the incident light. The filter consists of three linear variable filters and two order sorting filters on a common substrate. Each of the linear variable filter is employing a different spectral gradient and is designed as bandpass filters for a dedicated spectral range.

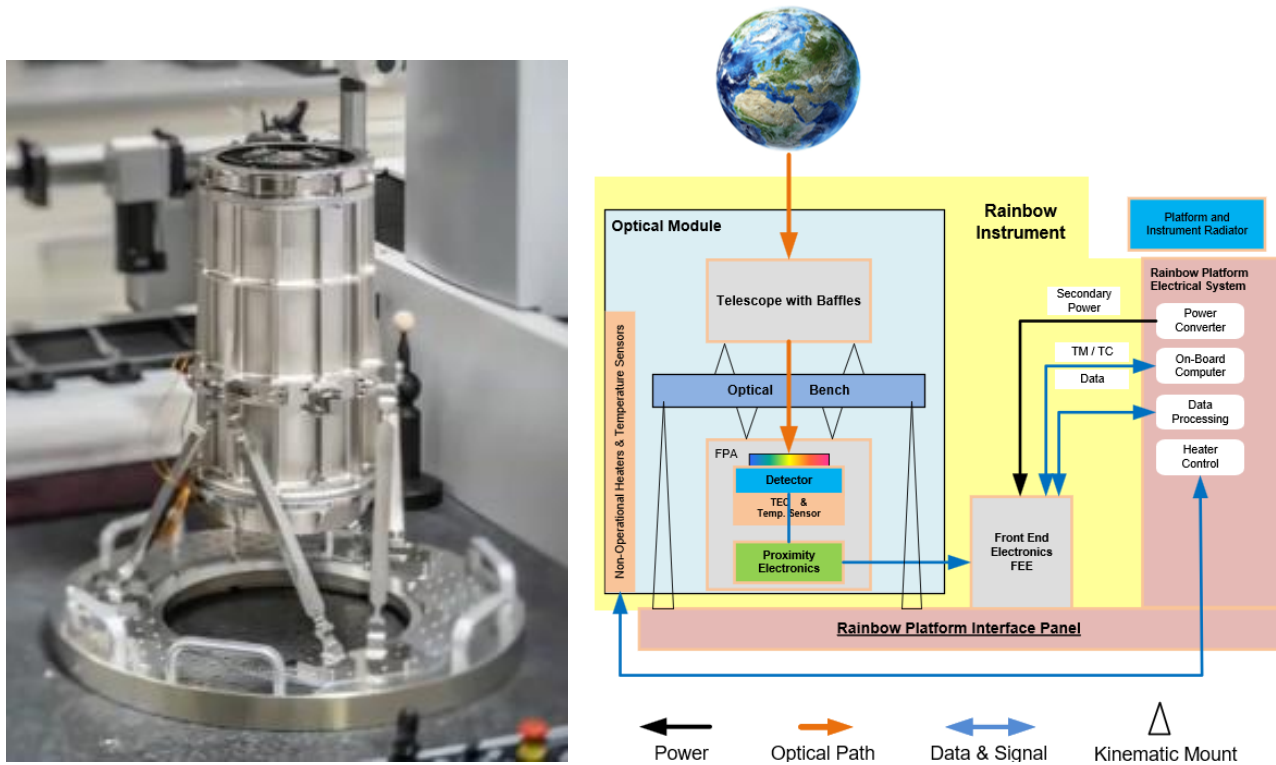


Figure 3: Rainbow Telescope after assembly (left; © IOF) and Functional Block Diagram (right)

A proximity electronics is attached close to the detector and performs filtering and amplification of the analogue detector signals before they are transferred to the FEE.

The FEE is controlled via a platform provided On-Board Computer (OBC). The platform also provides units that interface with the FEE to command the detector read-out and to read-out telemetry and image data.

The optical module itself is made of an instrument baseplate where the RC telescope and the focal plane assembly are attached to. The telescope is mounted on the Earth viewing side whereas the focal plane assembly sits on the opposite side. A hole within the baseplate lets the light from the telescope pass through to the detector.

The focal plane includes a detector mounting plate, the detector, on which the hyperspectral filter is attached to, and the detector proximity electronics. A detector built-in thermoelectric cooler is used to stabilize the detector at -20°C . The resulting temperature is monitored by a sensor and is then used on-ground to determine the detector signal offset.

The optical module is attached via kinematic mounts to the platform. The FEE is planned to be mounted in close proximity to the detector.

In order to get the ground coverage and revisit times required for the mission, several of the Rainbow instruments are required. Figure 4 shows the arrangement of 12 instruments on a common payload structure. Each of the instruments has a dedicated pointing direction to allow, with a small field-of-view overlap, to cover a large swath. The structure itself will be attached to the satellite.

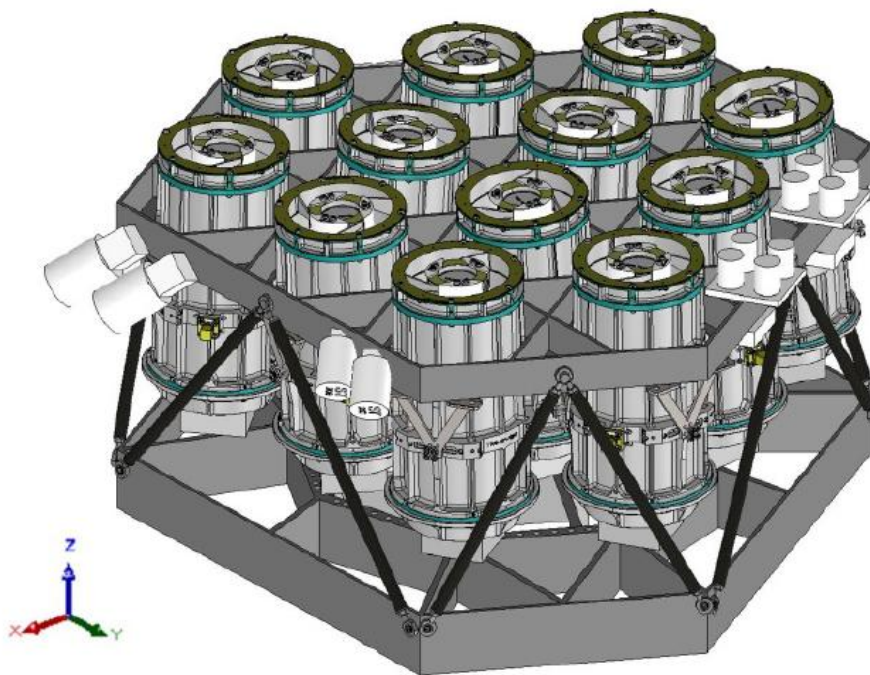


Figure 4: 12 Rainbow instruments mounted in a common satellite payload structure

5. FILTER MANUFACTURING

The compact linearly variable bandpass filter was developed by Fraunhofer IST. The spectral range from 440 nm to 1700 nm is covered by three monolithically integrated linear variable bandpass filters addressing the VIS (440–700 nm), NIR-1 (700–1120 nm), and NIR-2 (1160–1700 nm) regions [2].

The filters are fabricated by magnetron sputtering in an EOSS[®] coating system. The coater's turntable geometry with dual rotatable magnetron sources and plasma oxidation yields stable processes that enable the deposition of interference filters with more than 500 layers [3]. During the deposition, tailored shaper masks were used to generate steep thickness gradients. Digital twin simulations were employed to optimize mask geometries and deposition conditions, enabling gradients of up to 122 nm mm⁻¹ in central wavelength, or relative layer-thickness gradients of up to 27.8 % mm⁻¹. Accurate substrate positioning was achieved through dedicated carrier designs and micrometer-scale adjustment mechanisms, reducing positioning uncertainties to approximately 20 µm. To avoid spectral broadening of the bandpasses, the total spectral range was divided into three spectral ranges with separate bandpass coatings. These separate filter coatings were realized by micro structuring techniques using repeated UV lithography and lift-off processes. Even with layer thicknesses of up to 17.6 µm, sharp transitions with less than 25 µm were achieved. As a result, the sensor area is utilized optimally by the filter.

Optical characterization was carried out using a specially developed microphotospectrometer with a measurement spot size of approximately 50 µm in order to precisely measure the transmittance in all bandpass regions.

The filter achieves a maximum transmission of 89% and blocks unwanted wavelengths in the range from 400 nm to 1700 nm with an average of OD3. The measured transmittance of the three structured linearly variable bandpass filters is shown in Figure 5. To meet the high blocking requirements, the backside of the filter was coated with two dedicated interference blockers. By matching the blocking regions and the bandpass designs precisely, both the number of layers and the total layer thickness were reduced. The results demonstrate the feasibility of compact linearly variable bandpass filters for spaceborne hyperspectral imaging and establish a scalable process chain for future filter-on-chip instruments.

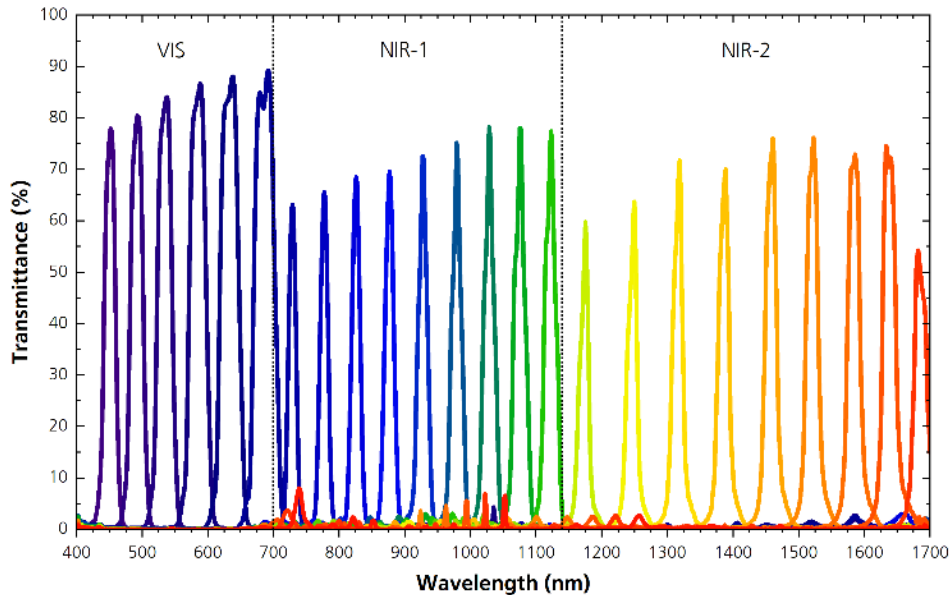


Figure 5: Measured transmittance from a spectrophotometer setup, showing the three structured linearly variable bandpass filters in the middle of one filter substrate.

6. FILTER DETECTOR INTEGRATION CONCEPTS

The Rainbow instrument mainly consists of a telescope and a filter-detector unit. The filter will be placed directly in front of the detector to avoid additional optical elements, e.g. relay optics. The filter will be hard mounted to the detector by e.g. gluing or clamping. A trade-off of suitable mounting concepts should identify a reasonable solution for an instrument breadboard.

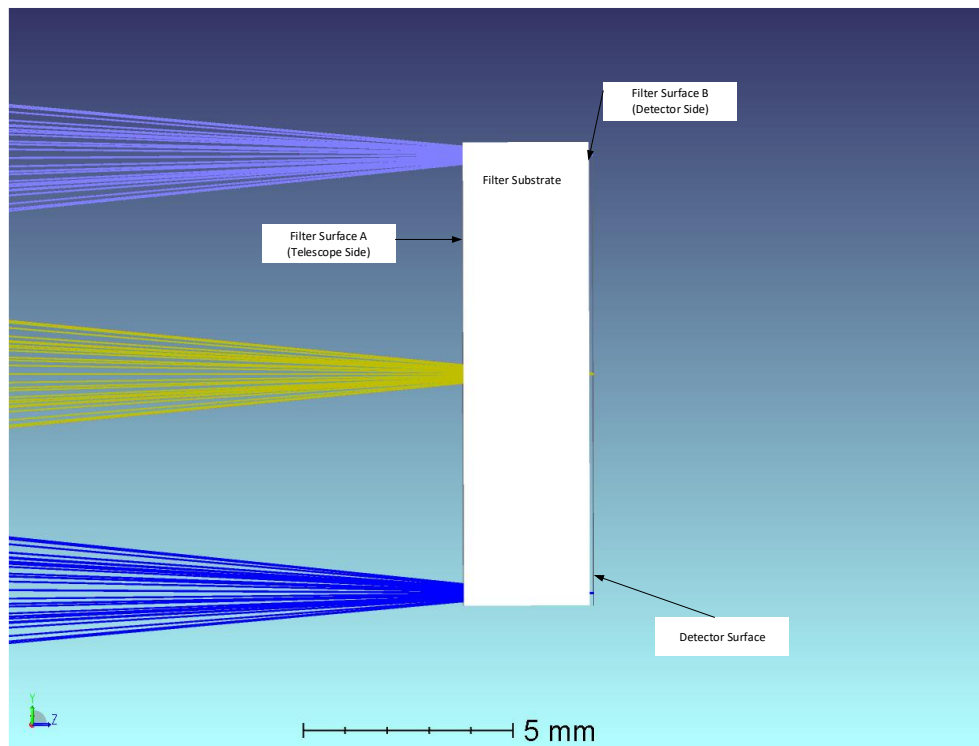


Figure 6: Filter to Detector Arrangement

General definitions

In order to develop and assess possible filter detector mating concepts the following general definitions are presumed.

The detector has to be used in acquisition mode during alignment, because of there are no structures which can be used for alignment onto the detector surface. The detector has to be connected to corresponding electronics and pixel read out software.

The filter geometry shall have the following dimensions: (13.0 mm x 11.5 mm x 2.5 mm (X-Y-Z-direction)). The filter substrate outside surfaces should be without chipping (polished) and should be black coated. The filter structures (bandpass, mask structures) will be used for active alignment of filter columns w.r.t. the detector pixel columns.

The gap in between the detector and the filter can be realized as:

- Air/vacuum gap
- Gap, filled with adhesive with defined refractive index (e.g. 1.56)

- Gap distance (thickness) maximum distance 0.2 mm in between upper surface of detector to lower surface of filter substrate for each option

The chosen sensors are available in two different packages by the detector manufacturer. The sensors geometry and surface planarity were characterized. For flight hardware the Cheetah-Package sensors were chosen.

Main topics for characterization were:

- Check Cheetah sensor packaging and geometry
- Sensor planarity measurements
- Sensor chip – geometry measurements
- Sensor chip – alignment structures „search“
- Bond wires – height measurements

The goal of the characterization was to define “stay out zones”, which are areas that are forbidden for handling and mounting of the filter, mounting frames, and integration/alignment Ground Support Equipment (GSE). As a result of this characterization the areas and structures, which will be used for filter mounting, were defined.

Design concept of mechanical mounting of filter substrate for integration

The integration baseline is to align the filter in Y-direction and Rz-rotation. The Z-direction and Rx and Ry-rotation will be defined by precise manufacturing of the filter frame and spacer elements. The position of the detector chip w.r.t. detector package interface will be characterized by measuring. The baseline integration concept of these mechanical integration options is similar. In all options the filter is fixed in a mechanical frame by adhesive bonding. The mechanical frame can be aligned with respect to the detector chip and will be fixed by one of the following options

- Mechanical clamping,
- Mechanical clamping supported by screwing

One option shows a possible design for the mechanical clamping of the filter frame onto the detector carrier.

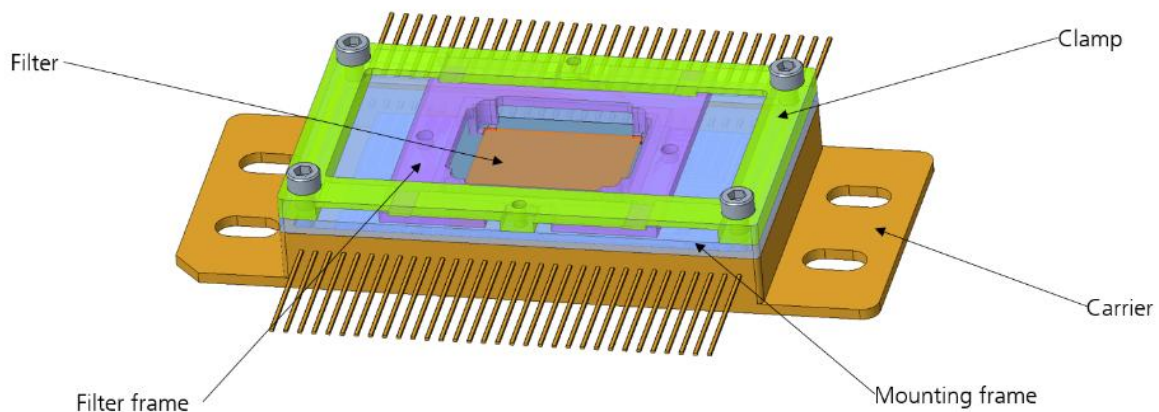


Figure 7: Schema of the mechanical clamping of the filter frame onto the detector carrier.

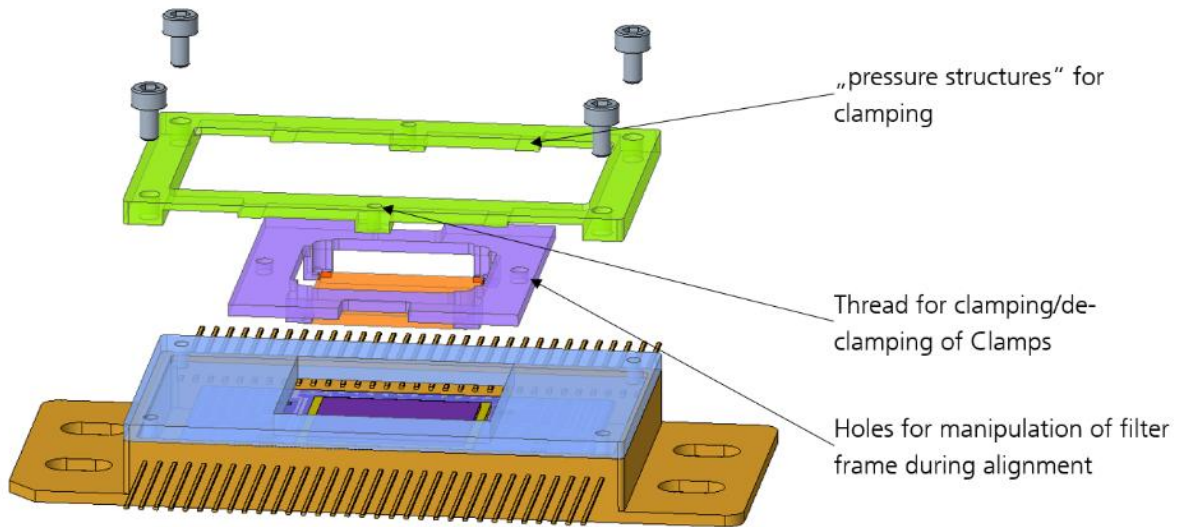


Figure 8: Exploded view of the mechanical clamping of the filter frame onto the detector carrier.

The Manufacturing of the mounting frame will be done in reference to the dimensions of the detector. Therefore, the distance and angle of the upper plane of detector carrier w.r.t. sensor surface needs to be measured, and the mounting frame has to be manufactured in a correspondingly tailored way.

In a second step the mounting frame needs to be fixed on the detector carrier by adhesive bonding. Afterwards, the distance of the upper plane of the mounting frame to the detector surface can be measured.

Depending on the result, the filter will be aligned (R_x , R_y und z) and glued to the filter frame (see Figure 9).

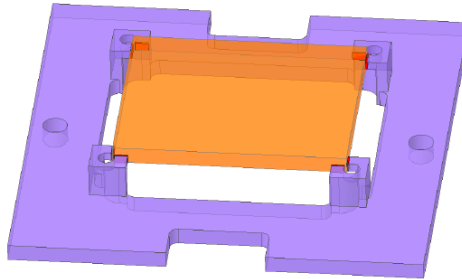


Figure 9: Aligned filter on filter frame.

Finally, the filter frame can be placed onto the mounting frame, aligned in R_z and y and fixed by screws. For alignment a specially designed GSE will be used (see Figures below). The GSE will be removed after integration.

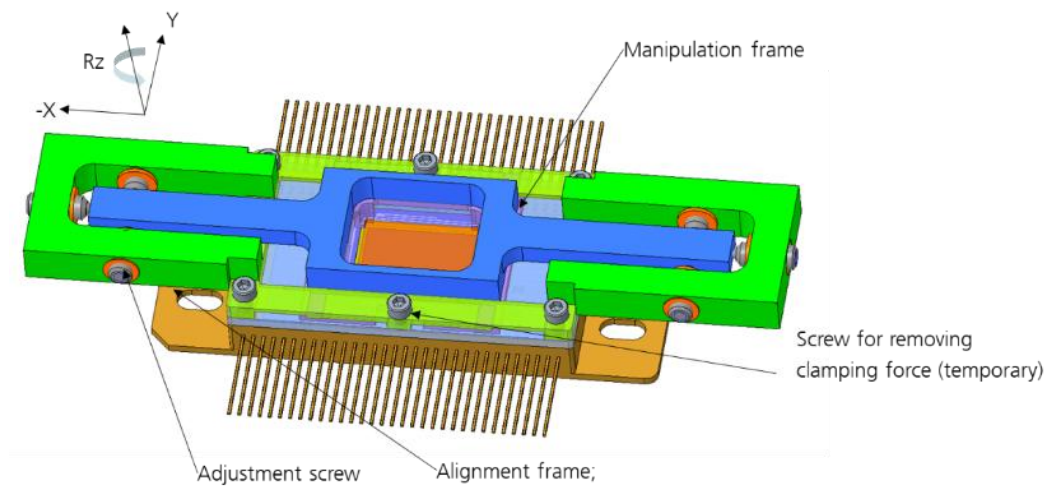


Figure 10: Alignment GSE for aligning the filter in front of the detector chip.

The second option shows a possible design for the screw supported mechanical clamping of the filter frame onto the detector carrier.

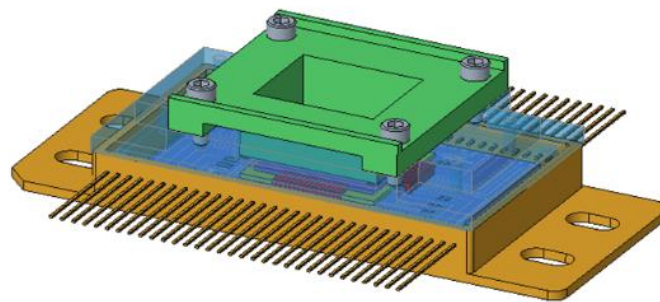


Figure 11: Schema of the screw supported mechanical clamping of the filter frame onto the detector carrier.

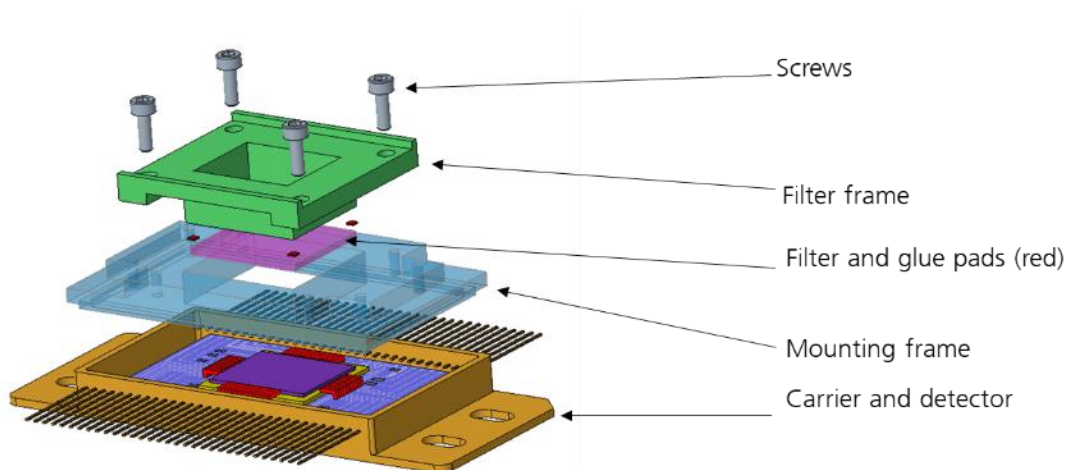


Figure 12: Exploded view of the screw supported mechanical clamping of the filter frame onto the detector carrier.

Like in the first option the manufacturing of the mounting frame will be done in reference to the measured dimensions of the detector. Therefore, the distance and angle of the upper plane of detector carrier w.r.t. sensor surface needs to be measured and the mounting frame tailored accordingly.

In a second step the mounting frame needs to be fixed on the detector carrier by adhesive bonding. Afterwards, the distance of the upper plane of the mounting frame to the detector surface can be measured. Based on these results, the filter frame can be manufactured accordingly. Finally, the filter will be aligned (Rx, Ry und z) and glued to the filter frame.

The filter frame is put into place onto the mounting frame within the detector package. The x- and y -position as well as the Rz rotation of the filter can be aligned using a specially designed alignment GSE with adjusting screws (see Figure 13). The GSE will be removed after integration.

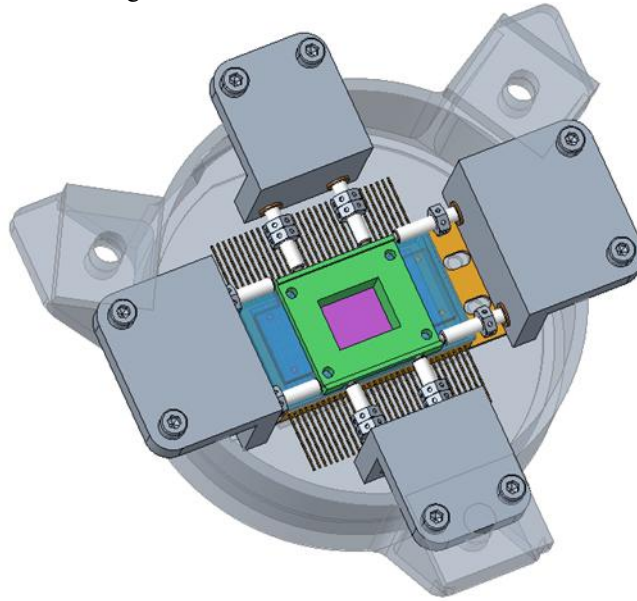


Figure 13: Alignment GSE for aligning the filter in front of the detector chip within the detector box.

After the alignment the filter frame is fixed to the mounting frame by screwing.

Design concept of direct mounting of filter substrate for integration

One option to use adhesive bonding for fixing the filter in front of the detector is the direct adhesive bonding of the filter onto the detector chip surface. Since the gap between filter and chip is filled with adhesive this option foresees no air/vacuum gap between the filter and the detector.

A defined volume of adhesive will be dispensed to the detector chip, which will define an adhesive gap of 10–80 μm thickness. When placing the filter, the adhesive will spread and fill the whole area between filter and chip. The filter will be handled, and its position will be manipulated by a gripper. The alignment verification of filter will be done using the pixel intensity information of the working detector. After alignment the adhesive will be cured. As the band pass filters will block UV-radiation, no UV-curing adhesives can be used. Thus, a 2-component optical epoxy adhesive with a refractive index of 1.56 will be used. The pot life of 3 hours guarantees enough time for integration and alignment.

When the air/vacuum gap is crucial for the function of the filter a second approach is possible to use the pros of adhesive bonding for the filter fixation.

By gluing the filter onto spacers an air/vacuum gap will be maintained. In the current Cheetah design the size of the spacer elements needs to be as small as 1.4 mm x 0.4 mm x 0.1 mm. The spacers would be positioned at the four edges of the detector sensor chip. Figure 14 shows one of the edges with a possible spacer position.

The spacer can be manufactured of glass or silicon wafers and will be fixed on the silicon chip by adhesive (e.g. 2-component epoxy or UV-curing adhesive). Once the spacers are fixed the integration of the filter can be started.

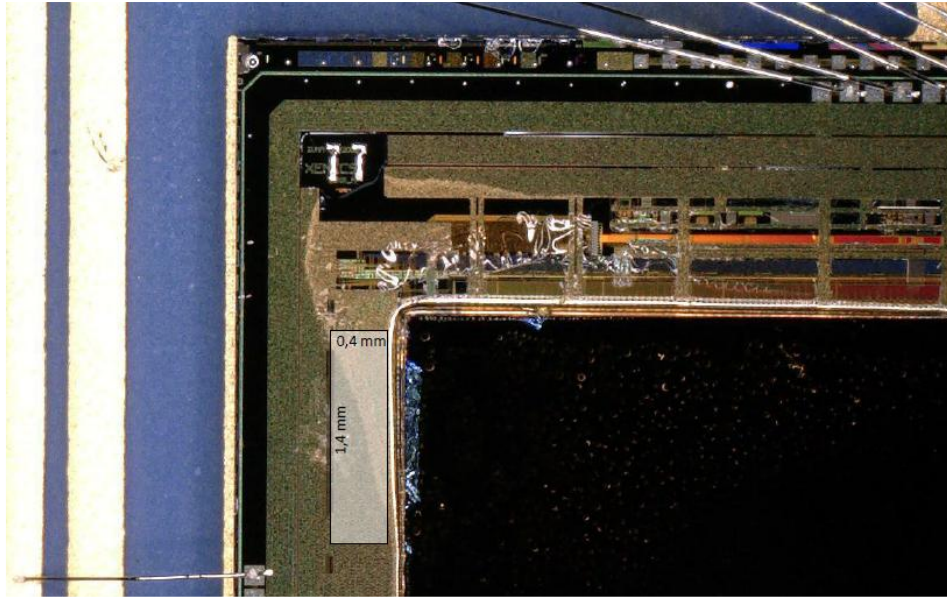
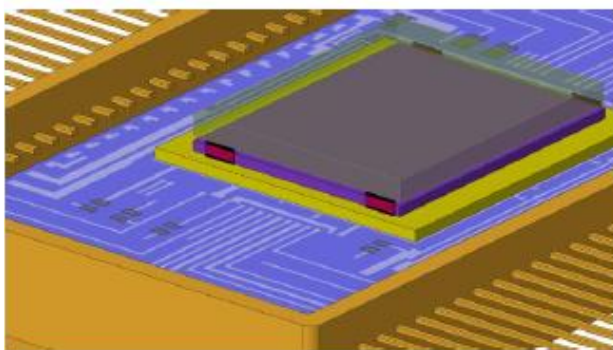


Figure 14: Area 1.4mm x 0.4 mm for spacer integration onto the Si-chip

To mount the filter a defined volume of adhesive needs to be applied onto the fixed spacers. Like in the first option the filter will be handled and its position manipulated by a gripper. The alignment verification of the filter will be done using the pixel intensity information of the working detector. After the filter alignment the adhesive will be cured.



Adhesive bonding areas (0.3x1.5x0.12)

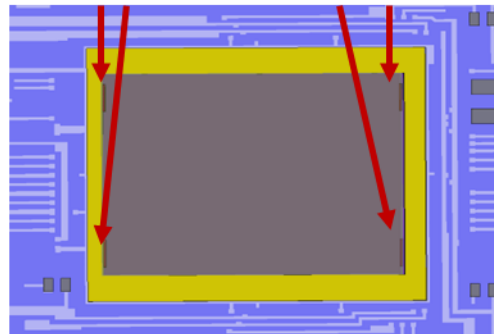


Figure 15: Filter integration to detector by adhesive bonding using spacers and air/vacuum gap

For the adhesive layer thickness less than $10\mu\text{m}$ is foreseen, adhesive application on peripheral areas will not be used for mechanical fixation.

The integration will be done in the following integration steps:

- Measuring sensor planarity
- Manufacturing of spacer elements to define the gap of less than $200\mu\text{m}$
- Adhesive bonding of spacer elements onto to Si-chip
- Dispensing of adhesive onto the spacer elements
- Integration of filter onto the spacer elements
- Alignment of filter in Rz and X-,Y-direction
- Curing of adhesive while holding filter in position

The lap shear strength of the adhesive joints was estimated. The mass of the filter was calculated to be approx. 0.369 g ($\rho = 2.201 \text{ g/cm}^3$; $14\text{mm} \times 12\text{mm} \times 1\text{mm}$). The quasi-static shock loads are defined to 35g; this results in a load of 0.129 N to the bonding areas. The minimum lap shear strength of adhesive will be 10 MPa. Using four spacers with 1.5mm x 0.3mm bonding area, which provides approx. 2 mm² bonding surface, results in 20 N bonding strength. Without considering any per ECSS required Margin of Safety (MoS)-factors, the estimated MoS is more than 150.

Trade-off – integration concepts

For the mating (assembly and alignment) of the detector and filter different concepts are considered in the trade-off process. The general trade-off criteria are:

Performance:

- Alignment and ground to orbit stability requirements

Environmental loads:

- Mechanical loads
- Thermal loads

Envelope – space for filter mounting:

Effort and costs for manufacturing and integration

All described options of filter detector mating meet the performance requirements and the requirements of environmental loads.

The integration options of mechanical clamping were not chosen, because of their complexity and the risk of thermal induced movements of filter w.r.t. detector.

The option of direct bonding of filter onto the detector surface was not chosen, because of the high risk and additional effort in filter design and filter manufacturing.

The chosen option is the adhesive bonding of the filter onto spacer elements using air/vacuum gap between filter and detector.

7. FILTER DETECTOR INTEGRATION RESULTS

An integration GSE was developed and implemented. Handling and alignment tests show the function of the alignment device. A user interface for calculating the alignment status was implemented and tested.

The filter to detector integration process was conducted using several structured filters and detectors. The results showed that the alignment of filters directly to the detector surface is possible to meet the specified alignment tolerances.

The GSE for filter integration will be used (see Figure 16). The GSE will use any available camera electronics (blue part) for detector-filter mounting. The filter will be gripped by an align able gripper. The alignment of filter in x-, y- and Rz-direction will be done manually, using the fine adjustment screws of the filter gripper unit.

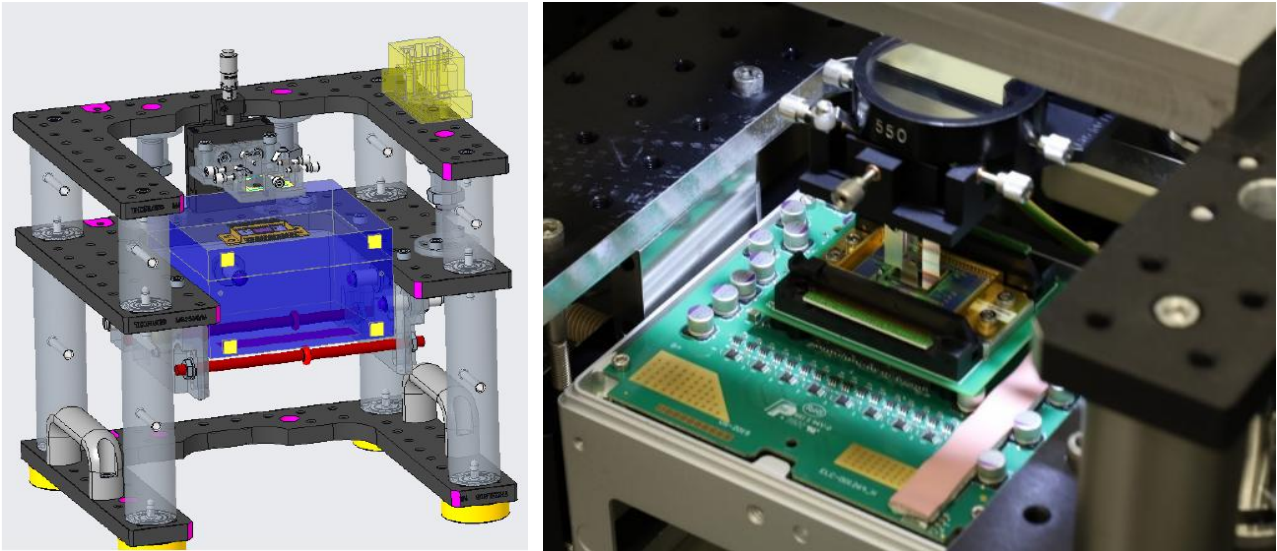


Figure 16: Integration GSE left CAD – right realized setup

The mechanical parts for GSE were manufactured. An ESD protected work space was installed.

Setup for filter alignment

The following setup for filter alignment was chosen after several alignment tests.

The illumination is done by an LED arrangement with lithographic structured diffusor plate. A 550 nm band pass filter (12 nm FWHM) was used.

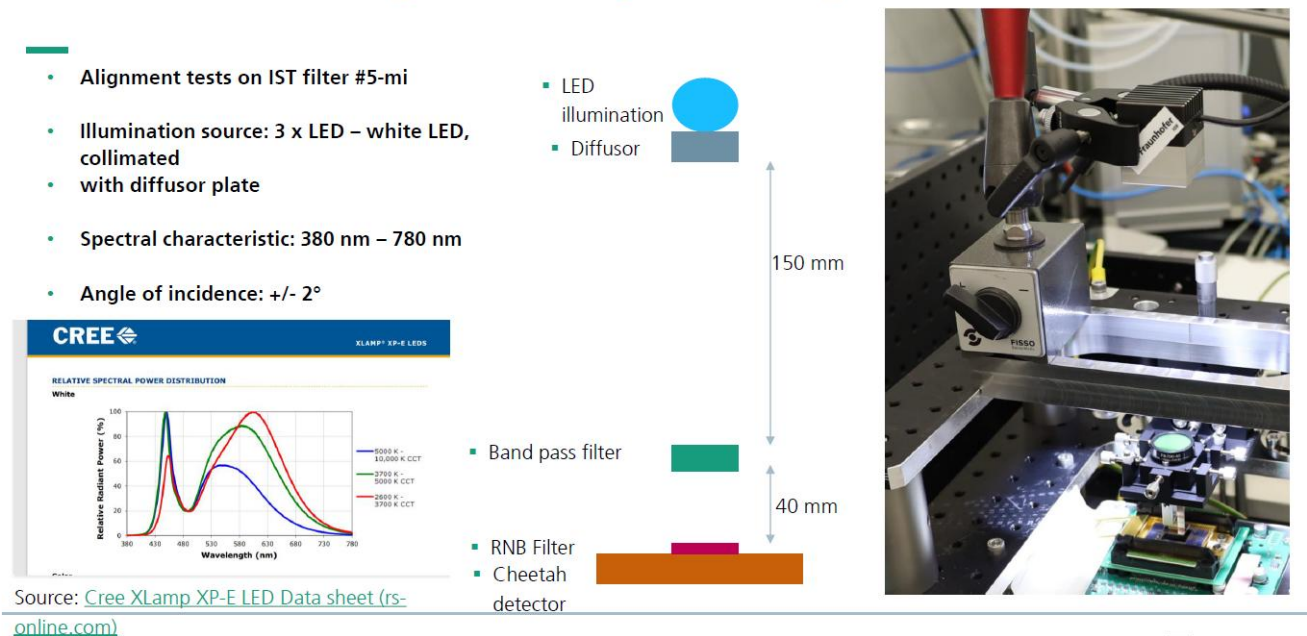


Figure 17: Filter alignment setup

The alignment was done by illumination of the detector with 550 nm spectral band. Only the line of 550 nm light, passing the structured filter, was used for alignment. The nominal position of the 550 nm band is defined to pixel number 49.2. The filter was aligned in rotation R_z and the nominal y-position of 49.2 pixel.

Image processing for filter alignment

The filter alignment status was monitored by image processing of the camera images. A developed software tool analyzes the pixel intensities of pixel rows and columns and give values for rotation Rz-angles and distance to the detector row 0. To minimize the detector noise, 50 to 100 images were taken and used for calculation of the filter position.

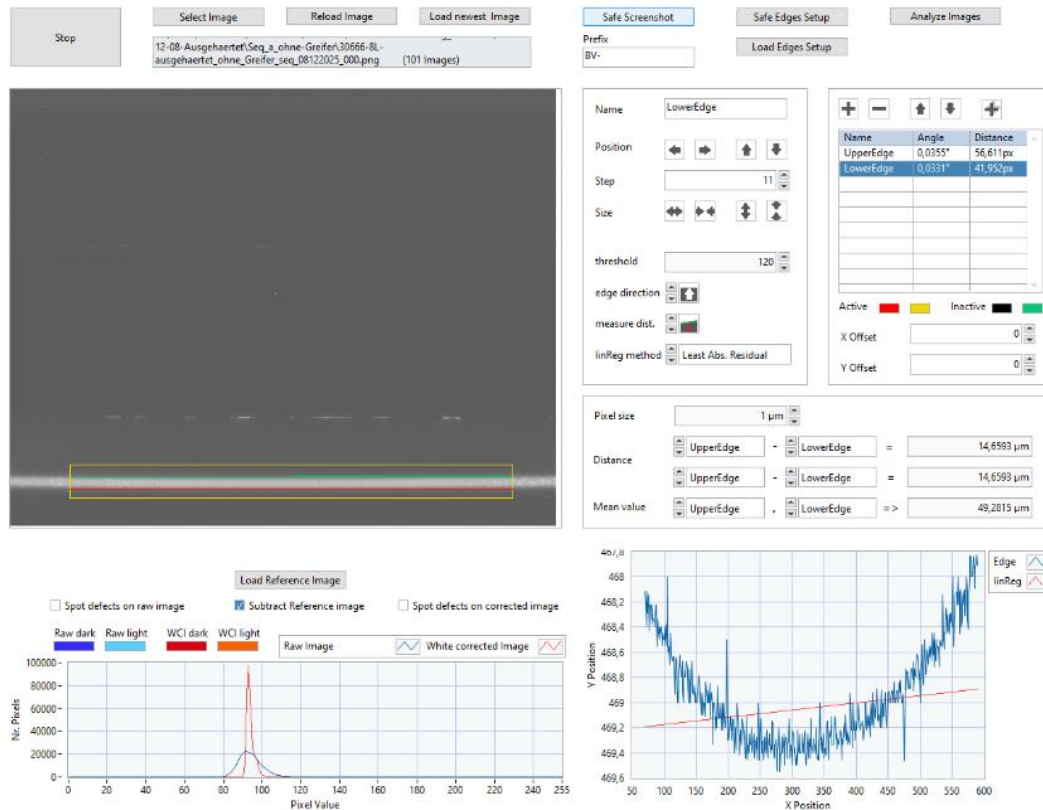


Figure 18: Alignment status after filter integration, after curing

The alignment status shows no deviation of 550 nm center line position (less than 0.06 pixel = 1.2 μm) after curing of adhesive. All alignment requirements were met.

A summary of alignment status according to required specification for all degrees of freedom is given in the table below:

Table 1: Alignment status of filter-detector

Degree of freedom	Spec. value	Test value	Result
X [mm]	± 0.050	<0.050	C
Y [mm]	± 0.004	0.002	C
Z [mm]	± 0.045	< 0.02	C
Z [mm] height	< 0.2	0.120	C
ROTX U [deg]	± 0.4	<0.05	C
ROTY V [deg]	± 0.4	<0.045	C
ROTZ W [deg]	± 0.04	0.035	C

After successful integration the detector was de-mounted from the camera. The detector window was closed for shipping, see figures below.



Figure 19: Detector with integrated filter, protection window opened

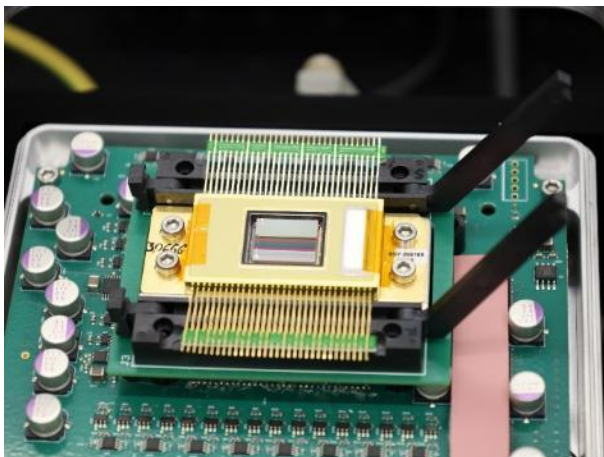


Figure 20 (left): detector with integrated filter, protection window closed

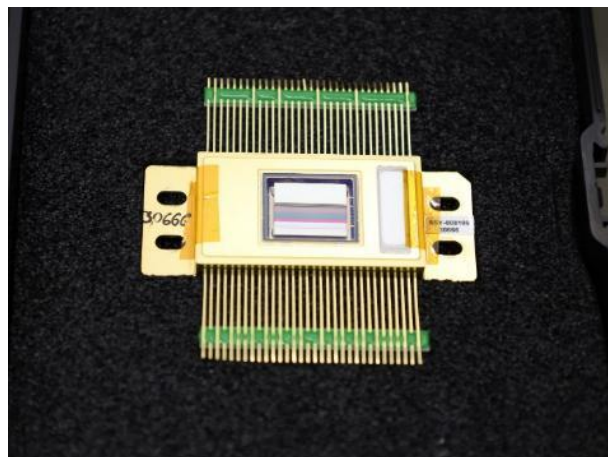


Figure 21 (right): detector with integrated filter, protection window closed, in transport box

The package lid is reversed in the images as the white stripe is a desiccant element to keep the interior of the detector free from moisture. Normally, it is face to the inside of the sensor package.

8. SUMMARY

The integration of a structured multi band filter onto a detector has been developed and successfully tested. Different options of integration concepts have been developed. The direct bonding of the filter onto spacer elements has been chosen as favorite option. The alignment requirements have been met. The analysis of mechanical loads shows that the mechanical requirements concerning shock and vibration loads are met. Thermal vacuum tests on representative samples proof that the thermal-vacuum load requirements are met.

The detectors with integrated filters can be used for function and performance tests in the Rainbow telescope assembly.

As a result of the Rainbow de-risking study, a cost-efficient process for filter to detector integration has been developed.

ACKNOWLEDGEMENTS

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