

CHIME's hyperspectral imager (HSI): status of the optical model (OM) and AIT process

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ABSTRACT

The Copernicus Hyperspectral Imaging Mission for the Environment (CHIME) will provide hyperspectral observations in the spectral range from 400 nm to 2500 nm to support environmental monitoring, sustainable agriculture, biodiversity assessment and raw material management [1]. The CHIME hyperspectral instrument (HSI) is based on a push-broom imaging spectrometer architecture consisting of a four-mirror telescope feeding three spectrometer subsystems (SPS), each coupled to a dedicated focal plane assembly (FPA).

Stringent mission requirements on modulation transfer function (MTF), spectral accuracy and spatial-spectral co-registration require accurate alignment between each SPS and its corresponding FPA. To de-risk the Proto-Flight Model (PFM) and Flight Model (FM) integration campaigns, an Optical Model (OM) was developed by OHB. The OM is used to validate the SPS-FPA alignment concept, the optical ground support equipment (OGSE), alignment procedures and associated data-processing algorithms under representative environmental conditions.

The alignment activities are performed under vacuum conditions with cryogenic cooling of the detector, enabling representative thermo-mechanical behaviour of the focal plane assembly. Dedicated OGSE including the Wide Range Adjustable Light Source (WiRAL) and the Spectrometer Slit Illumination Device (SpecSID) are used to provide spectrally tuneable illumination and precise slit-referenced beam positioning. A dedicated simulation framework was developed to verify the analysis chain and alignment methodology prior to execution of the optical campaign.

This paper presents the Optical Model configuration, the alignment methodology and the current status of the ongoing AIT campaign. Preliminary commissioning results including successful thermal-vacuum operation, OGSE stability characterization and first kernel-edge measurements demonstrate the readiness of the measurement infrastructure for the subsequent SPS-FPA alignment activities.

Keywords: CHIME, hyperspectral imaging, optical alignment, AIT, spectrometer, focal plane assembly, OGSE

1. INTRODUCTION

The integration of the focal plane assembly (FPA) onto the spectrometer subsystem (SPS) represents the most critical optical integration activity of the CHIME payload. The detector position relative to the SPS focal plane directly impacts image quality, spatial-spectral co-registration and geometric distortions such as smile and keystone. Consequently, the detector must be positioned and verified with micrometric accuracy while accounting for the thermo-elastic behavior of the assembly at operational temperature and environmental conditions. Cryogenic cooling is also required to suppress dark current levels that would otherwise lead to detector saturation during optical measurements. Prior to execution on flight hardware, these elements must be validated and the associated alignment procedures demonstrated. Figure 1 shows the SPS-FPA assembly, and the mechanical interface addressed by the alignment campaign. The SPS-FPA assembly and its role within the overall CHIME optical architecture are described in more detail in [2], and further details on the SPS optical design can be found in [3].

The alignment process requires simultaneous control of detector translations, clocking, focus and tip/tilt while operating in a representative thermal-vacuum environment. To address these challenges, an Optical Model (OM) representative of the SPS-FPA interface was developed by OHB. The OM provides a dedicated platform for the validation of the alignment concept, optical and thermal ground support equipment, data processing algorithms and measurement methodologies under representative operational conditions. Furthermore, it enables the development and validation of the AIT procedures that will later be applied during the Proto-Flight Model (PFM) and Flight Model (FM) alignment campaigns.

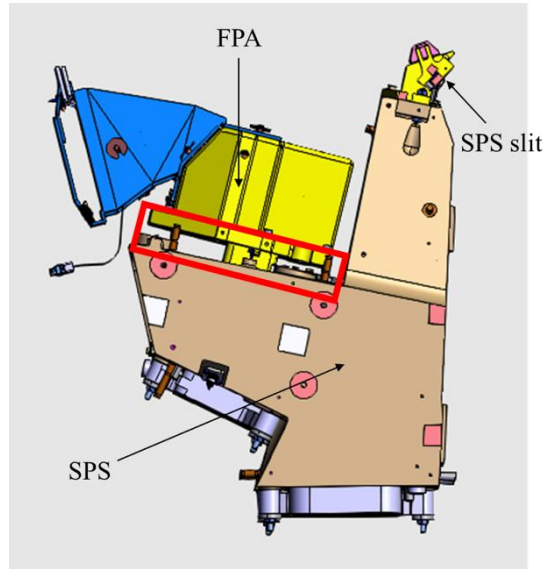


Figure 1. CHIME SPS-FPA assembly highlighting in red the detector-to-spectrometer alignment interface.

2. OPTICAL MODEL CONCEPT AND ALIGNMENT APPROACH

OM setup

The OM setup consists of an Engineering Qualification Model (EQM) SPS and an Engineering Model (EM) FPA, dedicated Optical Ground Support Equipment (OGSE) and Thermal Ground Support Equipment (TGSE) and electrical and data processing infrastructure. The SPS-FPA hardware is therefore representative of the flight optical design and of the mechanical and thermal interfaces relevant to the detector alignment process. To reproduce the operational configuration of the flight hardware, the alignment is performed inside a thermal-vacuum environment. During testing, the detector is operated at its nominal temperature of 175 K, ensuring representative thermo-elastic behaviour of the detector assembly and its mechanical interfaces. The resulting configuration allows verification of the detector position relative to the spectrometer focal plane under flight-representative conditions.

The optical illumination of the spectrometer is provided through a dedicated OGSE chain consisting of the Wide Range Adjustable Light Source (WiRAL) and the Spectrometer Slit Illumination Device (SpecSID). WiRAL generates monochromatic illumination tuneable over the complete CHIME spectral range and provides the optical input required for detector characterization and alignment activities. The output of WiRAL is coupled into the SpecSID, which generates the illumination on the spectrometer's slit and allows accurate control of its position within the spectrometer field. Depending on the measurement type, SpecSID can generate either a focused single-mode spot for spatial scanning or a multimode illumination field that over-illuminates the slit's width for spectral scanning. In addition to beam generation and positioning, the SpecSID incorporates optical metrology functions used to reference the projected beam position on the alignment interfaces on the spectrometer's slit with respect to the spectrometer's local optical coordinate system. The combination of WiRAL and SpecSID therefore enables repeatable generation of optical stimuli with known spectral content and spatial location throughout the alignment campaign.

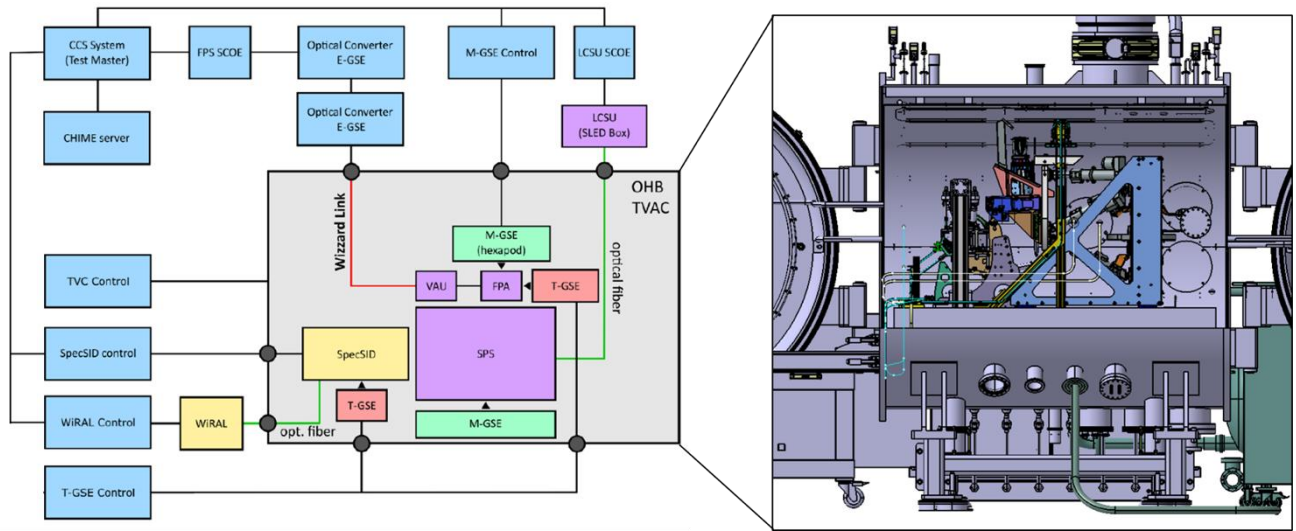


Figure 2. Schematic overview of the Optical Model optical setup.

A dedicated TGSE chain is used to establish and maintain the required thermal conditions inside the vacuum chamber. The thermal architecture combines a liquid nitrogen (LN₂) cooling circuit connected to the SpecSID thermal interface, a gaseous nitrogen (GN₂) cooling system coupled to the detector unit thermal strap, and a water-cooling circuit connected to the Video Acquisition Unit (VAU). Together, these independently controlled thermal interfaces provide a stable and representative thermo-mechanical configuration throughout the SPS-FPA alignment campaign. Figure 2 shows a schematic overview of the complete OM setup.

Alignment requirements

The OM design is driven by a set of mechanical positioning and optical alignment requirements allocated to the SPS-FPA AIT step. These requirements ensure that the detector is accurately positioned with respect to the spectrometer focal plane and that the resulting optical performance is compatible with the instrument-level image quality and co-registration budgets.

The in-plane requirements for FPA address detector positioning in the spectral and spatial directions, as well as detector clocking. The overall radial deviation of the radiometric centroid position with respect to the pixel center of any (FoV, wavelength) test point shall be $\leq 20 \mu\text{m}$. In addition, the rotational alignment between detector rows and the slit image, and between detector columns and the spectral dispersion direction, must be better than $36 \mu\text{rad}$. Compliance is verified through kernel-edge measurements acquired at multiple wavelengths and field positions, allowing the detector position and orientation to be derived from kernel-edge centroid analysis.

The out-of-plane alignment requirements are driven by image quality considerations. In accordance with the SPS-FPA alignment allocation, the combined effects of detector defocus and detector tip/tilt shall result in a maximum displacement of any detector point from the as-built focal surface of less than $\pm 35 \mu\text{m}$. This requirement is derived from the instrument-level MTF allocation and includes contributions from alignment uncertainties, OGSE measurement uncertainties and the detector flatness specification of $30 \mu\text{m}$ peak-to-valley. The different contributors are combined through a root-sum-square (RSS) budget analysis, resulting in an expected out-of-plane alignment accuracy of $30 \mu\text{m}$ against the allocated requirement of $35 \mu\text{m}$. Verification is performed through focus characterization using kernel-edge measurements at different positions of the detector along the optical axis.

Table 1. Optical Model alignment requirements.

Parameter	Requirement
In-plane detector position (X,Y)	The overall radial deviation of the radiometric centroid position with respect to the pixel center shall be $\leq 20 \mu\text{m}$.

	<i>Note: The ACT and ALT components are assessed jointly against this radial criterion.</i>
Detector clocking (Rz)	The on-ground alignment accuracy of the detector pixel rows with respect to the optical image of the slit onto the detector and the detector pixel columns with respect to spectral distribution of a single FoV shall be better than 36 μrad .
Out-of-plane displacement (focus + tip/tilt)	To achieve the MTF requirement on HSI level, the total out-of-plane translations (Tz) + rotations (Rx, Ry) shall lead to an out-of-plane displacement of each point on the detector by less than $\pm 35 \mu\text{m}$. <i>Note: This also includes the detector flatness (30 $\mu\text{m PV}$).</i>

Alignment approach

The alignment process to achieve the requirements is based on an iterative measurement-and-correction approach. Optical measurements are performed at detector level and analysed to determine the position and orientation of the detector relative to the as-built spectrometer focal plane. During the alignment process, the FPA is mounted on a dedicated alignment hexapod that enables controlled adjustment of its position and orientation. The applied displacements with respect to the as-built configuration are monitored using a set of confocal sensors, providing a quantitative measurement of the required alignment corrections. In-plane corrections, including detector translations and clocking, are performed using a dedicated push-pull adjustment GSE, while out-of-plane corrections are realized through calibrated shim insertion based on the measured alignment offsets. Following implementation of the required corrections, the optical characterization is repeated until convergence is achieved.

The SPS-FPA alignment relies on kernel-edge measurements performed in both the spatial and spectral directions. During the measurement, the projected optical spot is scanned across detector pixel boundaries in the spatial (X) and spectral (Y) direction, generating edge-response curves at different wavelengths and field positions. The spatial scans are performed by generating through the SpecSID a focused spot on the slit's plane and moving it accordingly in the X direction with the integrated hexapod. The SpecSID is equipped with multiple single mode fiber inputs, so that a focused spot can be generated on the slit's plane at different wavelengths within the 400 to 2500 nm range. On the other hand, spectral scans are performed by tuning the wavelength of the WiRAL source and illuminating the slit's aperture with a large square spot that illuminates the whole slit's width. A square spot illumination is achieved by using a square-core multimodal fiber in the SpecSID, which can guide multiple wavelengths simultaneously to parallelize the spectral scans. The tuning of the wavelength would then correspond to a scan in the Y direction of the detector unit. These measurements constitute the primary dataset used throughout the alignment process. For the in-plane characterization, the kernel-edge responses are analysed to determine the radiometric centroid position of the projected image with respect to the detector pixel geometry. The centroid evolution across wavelength and field is used to estimate detector translations in the spatial and spectral directions (X and Y) as well as detector clocking (Rz) relative to the SPS reference frame. The resulting alignment errors are corrected using the push-pull adjustment GSE.

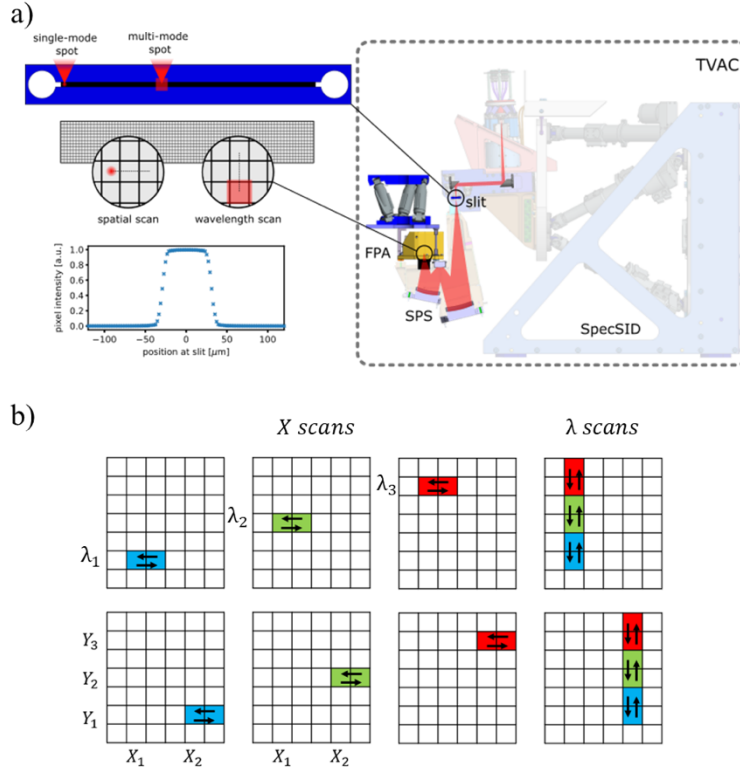


Figure 3. Overview of the optical measurements for the in-plane and out-of-plane alignment. a) Overview of the SpecSID illumination at the slit level. A focused single-mode spot is scanned along the across-track direction (ACT) or X, whereas a large multi-mode spot over-illuminates the slit's aperture to scan wavelength-wise along the along-track direction (ALT) or Y at the detector. b) X scans are performed by scanning the single-mode spot across the interface between two adjacent pixels, whereas lambda scans are performed by tuning the wavelength of the laser determining a scan of the imaged multimode-spot along the Y axis on the detector.

In addition, the width of the kernel-edge response is used for out-of-plane characterization. By performing measurements at multiple field locations, wavelengths and detector positions along the optical axis, the variation of the kernel-edge width can be monitored and minimized. The resulting measurements are sensitive to detector defocus as well as detector tip and tilt, enabling determination of the detector position relative to the nominal focal surface. Figure 3 illustrates the concept behind the spatial and spectral scans at the spectrometer's slit level.

In addition to the direct alignment requirements, the SPS-FPA alignment campaign includes the characterization of kernel-edge widths in the spatial and spectral directions, together with smile and keystone, against predefined optical success criteria. These metrics were derived from the instrument-level MTF, spectral resolution and geometric distortion requirements and therefore provide a direct indication of compliance with the allocated optical performance budget. For the ACT direction, Optical Engineering analyses establish the relationship between the measured kernel-edge profile and the corresponding spectrograph MTF by obtaining the Line Spread Function (LSF) through differentiation of the kernel-edge response, followed by Fourier transformation of the LSF [4]. Similarly, in the ALT direction, differentiation of the kernel-edge response yields the corresponding spectral LSF, from which the Instrument Spectral Response Function (ISRF) and the associated spectral-resolution performance are derived. The ACT and ALT kernel-edge width limits reported in Table 2 were derived from these analyses and represent measurable metrics for the allocated MTF and spectral-resolution requirements. Smile and keystone are derived from the radiometric centroid positions measured across wavelength and field points.

Table 2. Optical Model success criteria.

Performance metric	Success criteria
Kernel-edge X width (90%-10%)	$\leq 23.0 \mu\text{m}$ Corresponds to MTF ACT ≥ 0.67
Kernel-edge Y width (90%-10%)	$\leq 25.0 \mu\text{m}$ Corresponds to spectral resolution $\leq 10.7\text{nm}$, from which MTF ALT ≥ 0.60 is derived
Smile	$\leq 3.5 \mu\text{m}$
Keystone	$\leq 2.5 \mu\text{m}$

Data processing pipeline

Detector images acquired during the measurement campaign are processed using a dedicated software framework developed for SPS-FPA alignment and performance verification. The processing chain includes image preprocessing, kernel-edge extraction, determination of radiometric centroid position, kernel-edge width estimation in both the spatial and spectral directions, and the derivation of geometric performance metrics such as smile and keystone.

To verify the processing chain prior to execution of the optical campaign, a dedicated simulation environment was developed to generate synthetic detector images representative of the SPS-FPA alignment measurements. The simulator reproduces the projected illumination pattern at detector level, including kernel-edge responses at multiple field positions and wavelengths. From the generated images, the complete analysis chain is executed identically to real measurements, enabling verification of the processing chain. Figure 4 presents an example of the processing flow on simulated detector images.

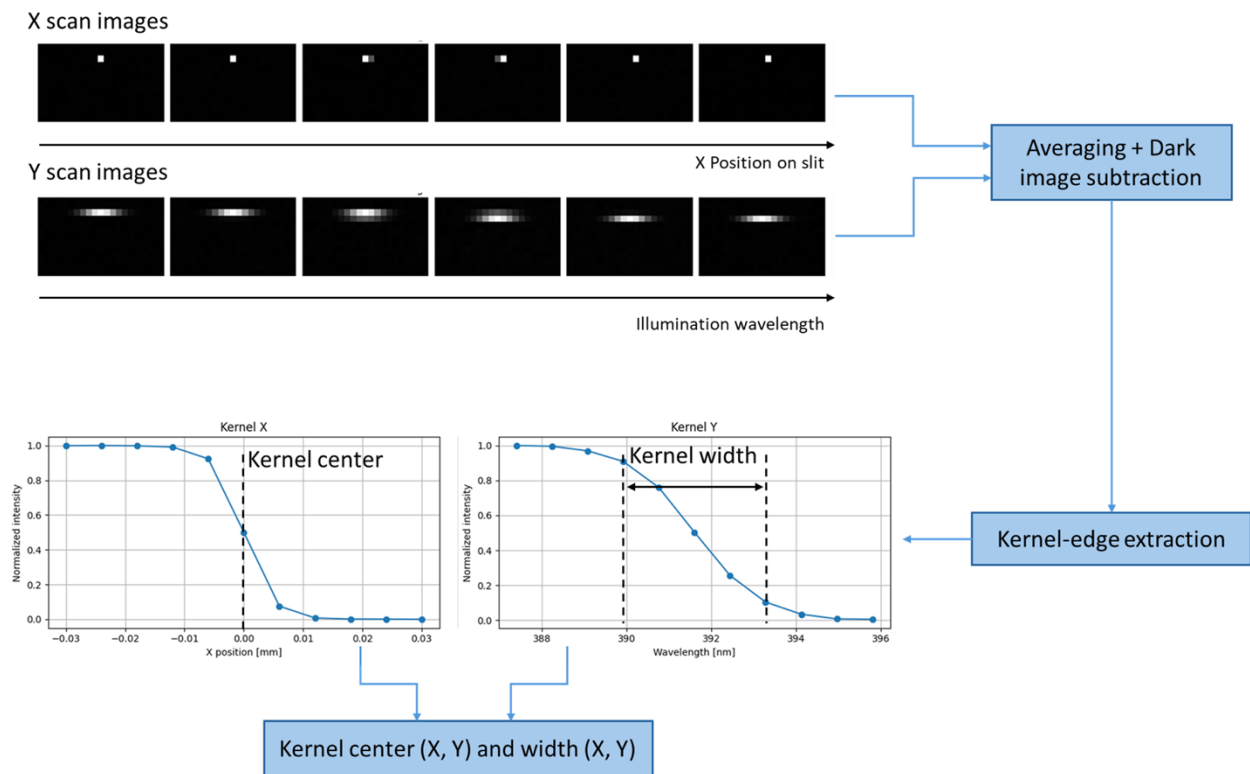


Figure 4. Example of data processing workflow of the kernel-edge measurements used for in-plane SPS-FPA alignment on simulated detector images. For each test point (corresponding to one field position on the slit and one wavelength), X scan images and Y scan images are acquired, by scanning the X position on the slit and tuning the illumination wavelength, respectively. The images are then preprocessed by subtracting a reference dark image acquired in absence of light on the detector. The resulting images are then processed, and kernel profiles are reconstructed for both scanning directions. The kernel profiles are reconstructed by monitoring the signal of a reference detector pixel, selected as the brightest pixel in the initial scan position, throughout the complete scan sequence. The extracted kernel centroid and width constitute the primary observables used for detector positioning and alignment verification.

The simulation environment enables verification of the data processing workflow and assessment of the measurement methodology prior to availability of the complete OM measurement dataset. In particular, it provides a means to verify the implementation and functionality of the retrieval algorithms used for centroid, kernel-width, smile and keystone estimation using representative synthetic measurements.

3. CURRENT STATUS AND PRELIMINARY RESULTS

At the time of writing, the Optical Model integration and commissioning campaign has progressed through the setup verification and preliminary measurement phases. The focus of the current activities is the verification of the test infrastructure, optical ground support equipment, detector operation under representative conditions, and the associated data processing framework prior to execution of the full SPS-FPA alignment campaign.

OM assembly and commissioning

The Optical Model has been successfully assembled and integrated within the thermal-vacuum test facility. Mechanical, electrical and thermal interfaces between the SPS, FPA, OGSE and supporting ground support equipment have been verified. In parallel, the thermal control architecture comprising the LN₂, GN₂ and water-cooling circuits has been commissioned and demonstrated its capability to achieve and maintain the required operating conditions for alignment activities.

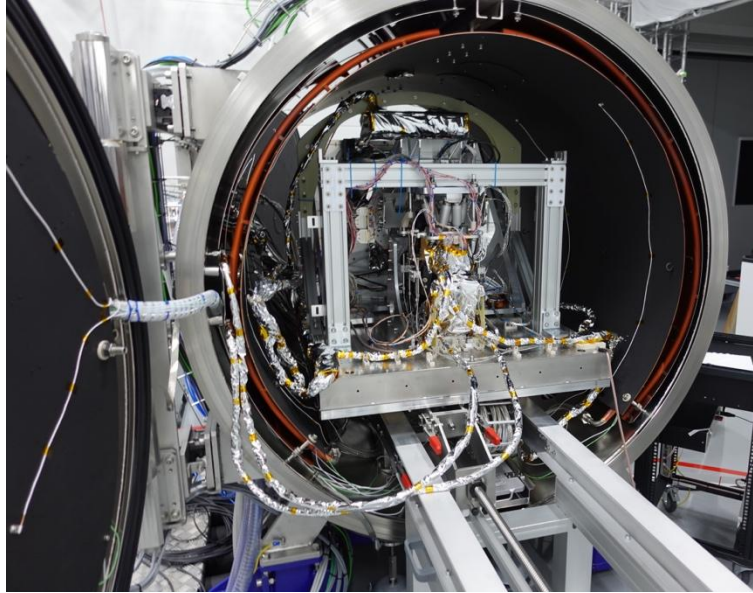


Figure 5. Integrated Optical Model setup inside the thermal-vacuum facility.

The commissioning activities confirmed the operability of all critical subsystems required for the alignment campaign and provided initial verification of the alignment workflow and measurement infrastructure.

The WiRAL and SpecSID OGSE have been commissioned and verified in the integrated configuration. Functional tests confirmed the generation of spectrally selectable optical stimuli and the capability to position and scan the projected beam with respect to the spectrometer slit reference frame. Initial measurements demonstrated successful optical throughput from the illumination source to the detector, confirming the operability of the complete optical chain used for SPS-FPA characterization. Figure 5 shows the whole OM setup placed in the thermal-vacuum chamber in ISO5 conditions.

Detector characterization and first kernel-edge measurements

Following successful thermal-vacuum commissioning, a series of preliminary detector tests was performed to verify detector operation and assess the readiness of the measurement chain. These activities included detector cool-down verification, thermal stability assessment, optical throughput confirmation and functional verification of the detector data conversion pipeline. During these preliminary activities, the detector was successfully cooled to approximately 188 K and maintained with a thermal stability of approximately ± 200 mK, while a preliminary positioning stability assessment performed after more than 5 h of operation indicated OGSE position variations of approximately 2 μm . The detector temperature was intentionally maintained slightly above the nominal operational temperature during the initial commissioning phase in order to reduce the number and depth of thermal cycles. Initial optical measurements were subsequently performed using the alignment OGSE. The resulting detector images confirmed successful optical throughput from the illumination source to the detector and verified operation of the detector readout chain under thermal-vacuum conditions. Figure 6 shows an example detector acquisition in which four wavelengths are simultaneously guided through the multimode fiber output and are visible on the detector, providing an initial verification of the optical illumination chain and detector response.

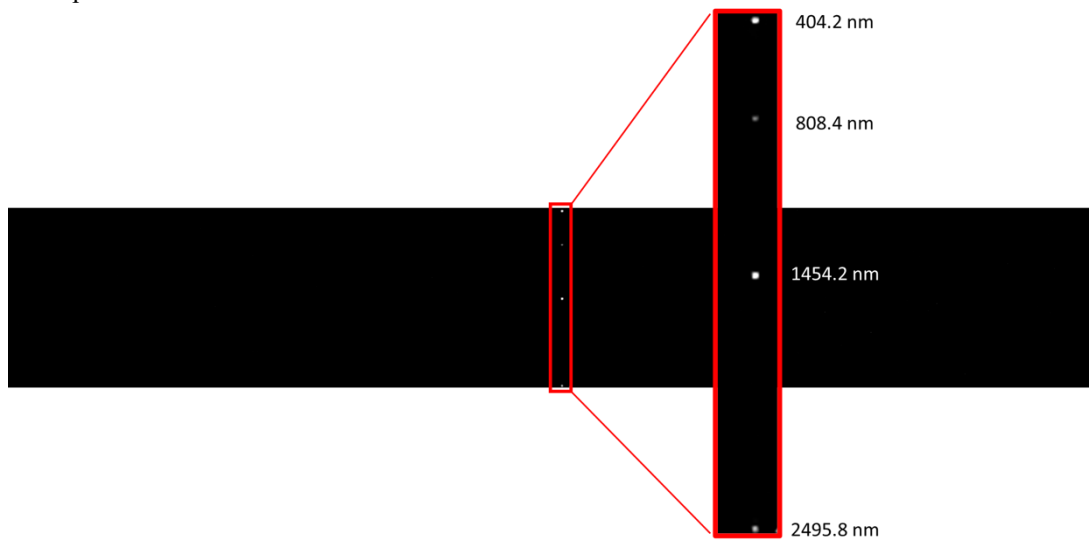


Figure 6. Example detector image acquired during preliminary OM measurements showing the four spots at different wavelengths simultaneously projected onto the detector from the multimode fiber output.

Moreover, the first kernel-edge scans were performed in both the spatial and spectral directions. These measurements were acquired by translating the projected illumination pattern across detector pixel boundaries and recording the corresponding detector response, as described in previous sections. The acquired images were processed using the operational analysis software, enabling extraction of kernel-edge profiles, radiometric centroid locations and kernel-edge width parameters. Figure 7 presents an example of the kernel-edge measurement for one field point and wavelength. The detector images during the X and Y scans are shown together with the corresponding extracted kernel-edge response. The retrieved centroid position and kernel-edge width constitute the primary observables used for SPS-FPA alignment and optical performance

verification. The preliminary measurements yielded 10%-90% kernel-edge widths of approximately 25 μm and 42 μm in the ACT and ALT directions, respectively. These measurements were acquired during the initial commissioning phase, prior to execution of the SPS-FPA alignment activities. The observed kernel widths therefore exceed the corresponding success criteria reported in Table 2, which is consistent with the expected pre-alignment state of the SPS-FPA assembly. Nevertheless, the acquired data demonstrate successful operation of the measurement and analysis chain and provide an initial demonstration of the capability to extract the key observables required for the subsequent alignment iterations.

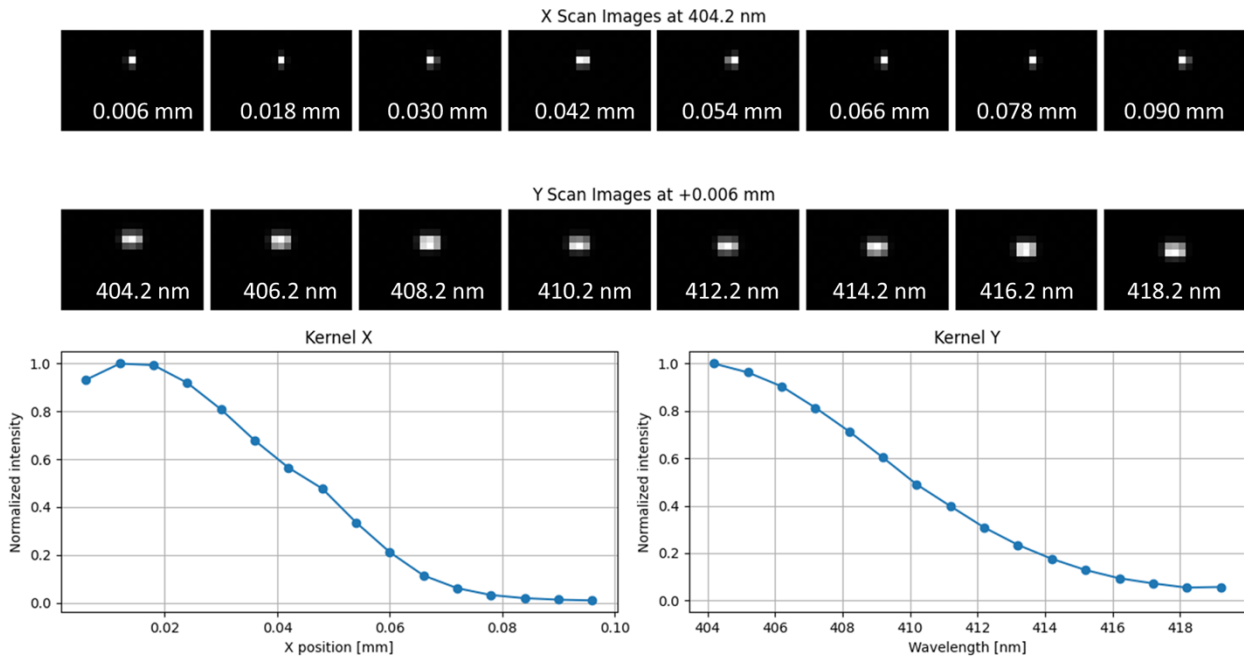


Figure 7. Example kernel-edge measurement. Up: detector image acquired during an X- or Y-direction kernel scan. Bottom: extracted kernel-edge response for centroid and width estimation.

4. CONCLUSIONS AND OUTLOOK

Following successful setup commissioning and completion of the preliminary verification activities, the SPS-FPA alignment de-risking campaign is currently ongoing. The OM has so far demonstrated the successful integration and operation of the thermal-vacuum test setup, OGSEs, detector acquisition chain and associated analysis software. Preliminary measurements have confirmed the capability to acquire and process kernel-edge data under integrated thermal-vacuum conditions. The remaining campaign will focus on the execution of the full optical characterization plan, including determination of detector position, clocking, focus, tip and tilt, as well as verification of the alignment success criteria. The quantitative assessment of SPS-FPA alignment accuracy and optical performance metrics remains part of the ongoing campaign activities. Upon completion of the campaign, the resulting measurements and operational experience will be used to refine alignment procedures, improve AIT efficiency and further reduce the technical risk associated with the CHIME PFM and FM SPS-FPA integration activities.

ACKNOWLEDGEMENTS

The CHIME Phase B2CDE1 contract is carried out as part of the Copernicus Programme, which is funded by the EU and ESA. The authors would like to thank the entire CHIME OM AIT team at OHB System AG for their support during the integration, commissioning and operation of the setup. The authors also acknowledge the support of the European Space

Agency (ESA) and Thales Alenia Space France throughout the development and execution of the CHIME Optical Model activities.

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