

Altius flight model preparation: from subsystems to instrument integration

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ABSTRACT

The Altius (Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere) mission, an Earth observation program led by the European Space Agency (ESA), is designed to deliver near real-time measurements of ozone, NO₂, and aerosols in the atmospheric limb between 0km and 100km altitude with a vertical resolution of approximately 1 km. The mission is developed by a consortium with Redwire as the prime satellite contractor and OIP as the prime instrument contractor. Operating from a sun-synchronous orbit at about 700km altitude, ALTIUS will observe the bright limb during the day and use stars and the sun as light sources at night. The satellite is scheduled for launch in 2028 aboard a Vega-C launcher.

The Altius payload consists of three hyperspectral channels: two based on Acousto-Optic Tuneable Filters (AOTFs) covering the Visible (444–675nm) and Near-Infrared (600–1020nm) ranges, and one using a cascade of Fabry-Pérot Interferometers (FPI) in the Ultraviolet (250–355nm). The use of tuneable active spectral filters enables Altius to achieve a spectral resolution between 1 nm and 10 nm, while simultaneously capturing a full 100km × 100km image of the limb. The instrument, with a mass of approximately 70 kg, is integrated onto a platform, resulting in a total satellite mass of 266kg. Its versatile operational concept allows for multiple observation types through various lines of sight.

This paper presents the Assembly, Integration, and Verification activities executed on the flight model of the instrument, from subsystem and active filter testing to channel assembly and integration. The challenges of channel integration and alignment, including the co-alignment of the three channels and multiple lines of sight, are discussed, along with the image quality figures achieved and the main difficulties encountered. Specific lessons learned from the use of active filters in the instrument are highlighted. The paper also provides an overview of the next steps following the alignment process, including the upcoming environmental test campaign (EMC, vibration, TVAC) and the calibration campaign scheduled for early 2027, before the instrument is assembled onto the spacecraft in preparation for the 2028 launch.

Keywords: European Space Agency, ALTIUS, limb, tuneable filters, AOTF, Fabry Perot Interferometer, Tuneable Filters, Alignment, Verifications

1. INTRODUCTION

ALTIUS Mission, now entering its final integration activities, is meant to support observations of the atmospheric limb with moderate spectral resolution over wavelengths from the UV to the NIR. Its main scope will be the mapping of the ozone atmospheric distribution, thanks to a high vertical resolution imager payload. A near global coverage of the ozone concentration will be provided, as the mission accommodates three observation modes: Bright Limb (BL) where the instrument will image light scattering by the atmosphere, Solar Occultation (SOO) and Stellar Occultation (STO) where the instrument will respectively image the Sun or stars going through the atmosphere [1].

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The ALTIUS platform is based on a PROBA-P-200, an autonomous, three-axis stabilised platform, integrating an extended ADCS system. It enables a high degree of manoeuvrability for the observations modes above-mentioned. The Instrument for the mission will be mounted on top of the platform deck which will fly in a Sun-synchronous orbit at an altitude of 668km, achieving the global coverage in a three-day revisit cycle.

ALTIUS is funded mainly by Belgium with contributions from Canada, Luxembourg and Romania with Belgium-based prime contractors. The satellite is built by Prime contractor Redwire while OIP Sensor Systems is the prime contractor for the instrument. The ground segment development is led by Spacebel with scientific support from the Belgian Institute for Space Aeronomy (BISA) and the University of Saskatchewan (USASK) in Canada.

2. ALTIUS PAYLOAD DESCRIPTION

The ALTIUS Instrument is composed of an Optical units (OU) and electronic boxes (CCU) as illustrated in Figure 2-1. The OU includes three independent spectral imagers, later-on called channels, in one single structure. Each imager contains an active spectral filter with a 2D array CMOS based focal plane enabling 2D imaging covering all observation modes over a total of seven different line of sights. Each channel has its own CCU box sitting next to the OU controlling focal planes, spectral filters and other electro-optical elements. The main geometrical, radiometric and spectral performances to be achieved by the instrument have been extensively reported in [1] and will not be rediscussed in there.

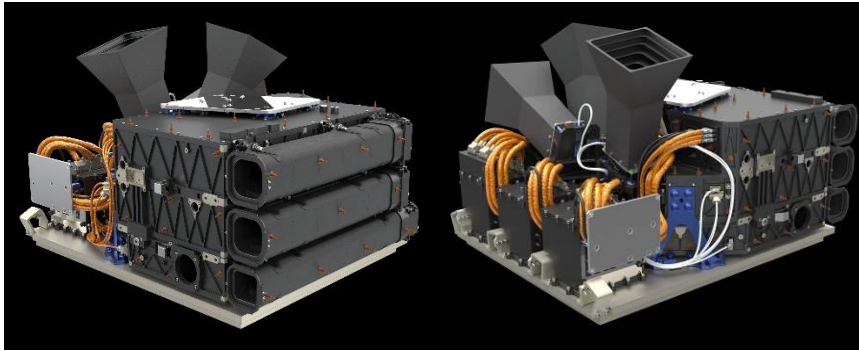


Figure 2-1: ALTIUS Instrument Optical bench and electronic boxes

UV channel

The UV channel, covering the range between 250nm and 355nm uses as spectral filter a cascade of four Fabry-Perot Interferometers (FPIs). The optical layout of the ALTIUS UV channel is based on an afocal design and merges two distinct optical paths. One path is to perform BL and SOO measurements, the second is for STO observations. This distinction was motivated by the maximum FPIs clear apertures of the FPIs reachable while maintaining the exceptional flatness and parallelism of the mirrors (to the nm level) necessary to achieve the spectral properties for the instrument. For bright limb observation, where atmospheric signal is intense, the 12 mm pupil limitation of the FPI assembly is acceptable to reach the necessary SNR. In the stellar occultation path, signal is faint and an increase of the effective SNR is necessary. This is done at the expense of a reduction of the channel Field of view, by coupling the bright limb path to an entrance pupil of 62mm diameter using a magnifying optical system [1]. Finally for solar occultation, the signal is very intense and shall be attenuated by a neutral density filter to prevent saturation of the detector. The coupling between the optical paths for each observation mode is then done by a mechanism whose arm contains a flat flip mirror and a neutral density filter holder, switching across an orbit between the bright limb, the Solar occultation and the stellar occultation mode.

Table 2-1: Optical design first parameters for the UV channel

PARAMETER	UNITS	BL/SOO	STO
field of view	mrاد	34 x 34	6.3 x 6.3
entrance pupil diameter	mm	12	62
total focal length	mm	106	568
StO optics magnification	mm	-	5.38
intermediate image size	mm	-	7.1 x 7.1
image size	mm	3.591 x 3.591	3.591 x 3.591

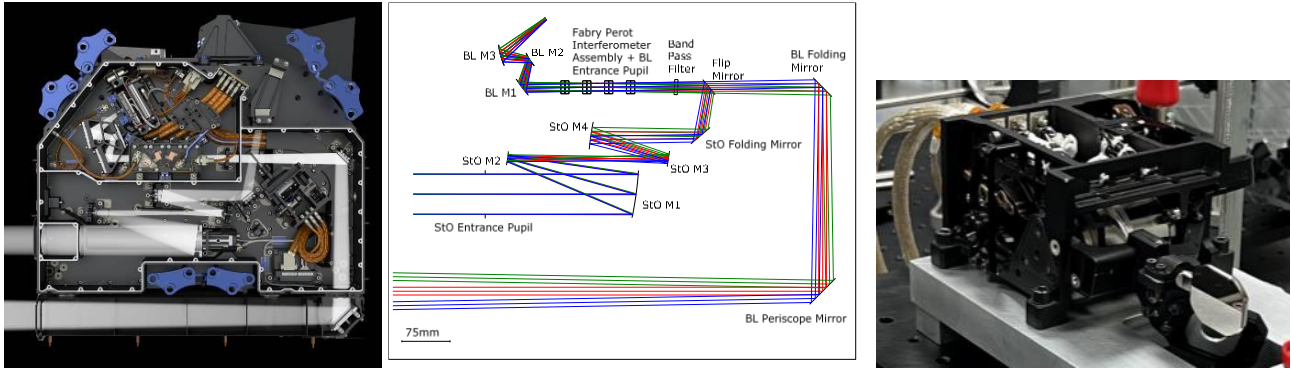


Figure 2-2: (top) ALTIUS UV channel layout (bottom) UV mechanism allowing switch of the optical paths

The UV spectral filter assembly consists of four Fabry-Pérot interferometer (FPI) units arranged in cascade. Each FPI is optimized for a specific portion of the instrument operating wavelength range and contributes to the overall spectral filtering function of the assembly. The cavity mirrors are implemented as semi-transparent dielectric Bragg reflectors based on alternating hafnium dioxide (HfO_2) and silicon dioxide (SiO_2) layers. Depending on the FPI unit, the mirror design comprises either nine or eleven layers, with the Bragg reflector center wavelength tailored to the corresponding spectral region. The required wavelength coverage and out-of-band rejection could not be achieved with a single cavity design, leading to the adoption of four spectrally optimized FPIs operated in cascade. The combination of four FPI units enables the required spectral selectivity and out-of-band rejection across the full UV operating range.

Each FPI unit comprises two substrates with the Bragg mirrors forming an optical cavity, together with integrated electrodes and piezoelectric actuators for cavity control. The piezoelectric actuators provide spectral tuning of each FPI over the operating range. Gap sensing using integrated capacitive measurement electrodes, combined with dedicated control electronics [4], is used to regulate the cavity spacing and minimize residual mirror-tilt errors. This closed-loop control enables the required spectral stability to be maintained over the full operational temperature range of the mission.

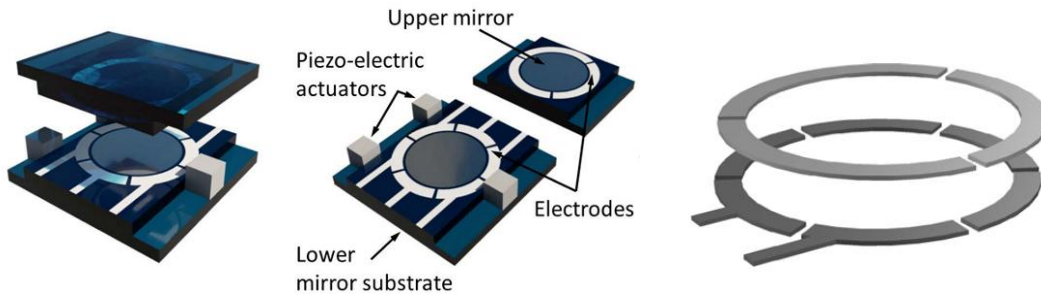


Figure 2-3: FPI cavity assembly stack

Beyond the FPI assembly itself, the UV channel optical system contains several imaging and beam-folding mirrors that guide light through the instrument. The optical design relies on super-polished nickel-plated mirrors, except for the STO first mirror, made of aluminium 6061 and only diamond turned. To enable spectral rejection of the visible light, not filtered by the FPIs, it was necessary to develop for those mirrors specific cold coatings whose development suffered various difficulties and required multiple iterations of development, testing, and qualification [3]. Compromises had to be made to mitigate the effect of the coating on scattering, wavefront error, spectral properties, while ensuring environmental qualification. The final configuration of each metallic mirror is a mixture of different coatings.

Table 2-2: Mirrors coating configuration of the UV channel

Mirror name	Flight mirrors coating type
UV-CHANNEL PERISCOPE MIRROR	Alflex
ALTB2 UV BL FM	Alflex
ALTB2 UV CHANNEL STO MIRROR M1	Alflex
ALTB2 UV-CHANNEL-ST MIRROR M2	Black
ALTB2 UV-CHANNEL-ST MIRROR M3	Black
ALTB2 UV STO4 MIRROR	Black
ALTB2 STO FOLDING MIRROR	Grey

MECHANISM FLIP MIRROR	Grey
UV-CHANNEL-BL MIRROR 1	Black
UV-CHANNEL-BL MIRROR 2	Black
UV-CHANNEL-BL MIRROR 3	Black

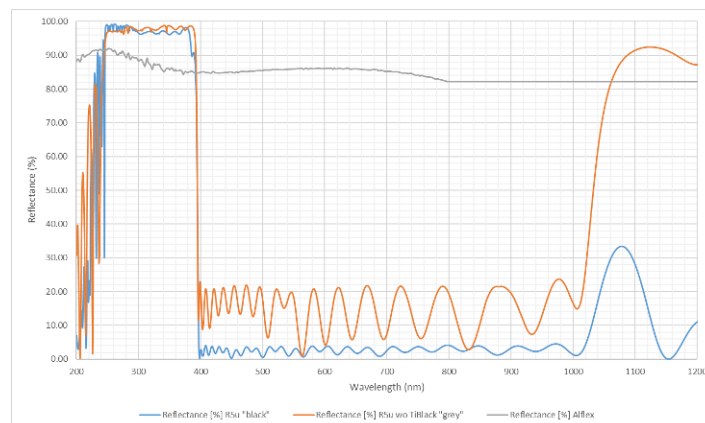


Figure 2-4: Reflectance curves of the different type of UV mirror coatings used in UV channel

The VIS wavelengths were further filtered by the integration of a bandpass filter in front of the FPI assembly with a dedicated dielectric coating also developed for the project. Together, these elements provide a visible-light rejection ratio of 10^{10} throughout the optical path to the detector.

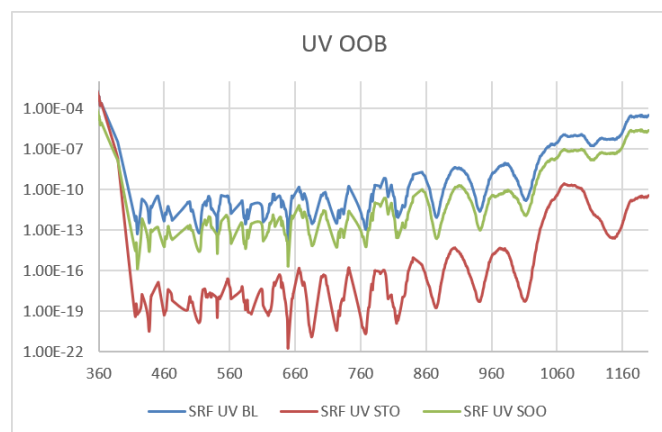


Figure 2-5: Reflectance of the VIS/NIR band through the UV optical design

The Focal Plane Assembly ensures filtered light detection using a CIS115 CMOS sensor with AR coating adapted for the UV range, developed by Teledyne-E2V in its VIS version for the JANUS project [5]. Each electro-optical element of the UV channel OU is controlled from the CCU unit by a dedicated PCB.

VIS and NIR channels

The VIS and NIR channels are sharing quasi-identical optical concepts, based on an AOTF as spectral filter, integrated in a confocal telecentric optical design. The VIS channel covers the wavelength range between 440nm and 670 nm while the NIR covers 600nm to 1020nm. A front-end optic (FEO) module composed of three mirrors generates an intermediate image plane behind an AOTF crystal which is imaged onto the CMOS detector CIS115 by a three mirror back-end optics relay design. The AOTF is itself in-between two 90°-oriented wire grid polarizers, allowing to select the proper incident polarization of light and rejecting for a part the order zero of diffraction which could cause straylight across the optical

path. The main difference between the two channels is the AOTF itself and the lens which is integrated in the front-end optics (FEO) allowing to correct for the AOTF induced chromatic aberration.

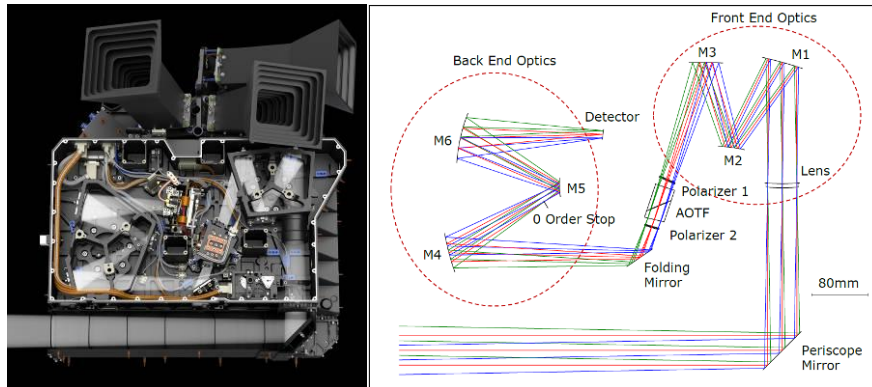


Figure 2-6: NIR Channel layout

A unique optical path with a 42mm entrance pupil diameter enables to support all observation scenarios and for solar occultation; like for the UV channel, a mechanism is used to position a neutral density filter in front of the optical path.

Table 2-3: Optical design first order parameters for the VIS and NIR channels

PARAMETER	UNITS	VIS	NIR
field of view	mrad	35 x 35	
entrance pupil diameter	mm	□42 & 34.5x42	□42
total focal length	mm	301	
front end optics focal length	mm	537	
intermediate image size	mm	18.8 x 18.8	
back end optics magnification		0.56	
intermediate pupil size	mm	11.4x17.6	13.7x17.7
image size	mm	10.521 x 10.521	

The optical design for the VIS and NIR channels offers more freedom to achieve spectral, radiometric and geometric requirement for the mission observations thanks to the 20x20mm clear aperture reachable with a large tellurium dioxide AOTF. UV channel, samples the 100km atmosphere squared scene over 170 equivalent pixels in line with the mission needs while the VIS and NIR channels offer a higher spatial sampling the same scene over 501 equivalent pixels.

3. SUBSYSTEMS ASSEMBLY AND TESTING

Mirrors manufacturing and tests

All metallic mirrors for the three channels were designed by OIP and manufactured by the Belgian company AMOS. The coating activities were for the VIS/NIR channel, by CILAS and for the UV channel by OBJ.

For the VIS and NIR channels, mirrors are based on RSA443 AlSi blanks, first diamond turned then coated with NiP to be further polished in order to try to achieve a roughness below 1.5nm RMS over the frequency between 1.5mm⁻¹ and 100mm⁻¹. The required surface roughness was achieved on all manufactured mirrors with as a main difficulty, to maintain the surface quality aligned with the needs during the polishing iterative process.

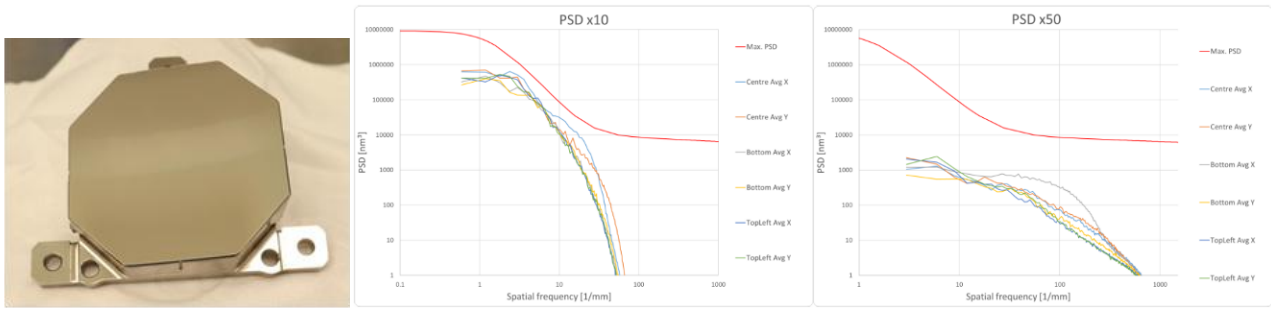


Figure 3-1: Typically achieved PSD for the VIS and NIR mirrors

All mirrors were then integrated and aligned in their respective three mirrors mechanical assemblies using a typical double pass interferometer setup. The alignment approach, co-engineered to fit with the mechanical design, was exceeding expectations for all optical properties including focal length on FEOs, magnifications on BEOs, distortion and line of sight of each module.

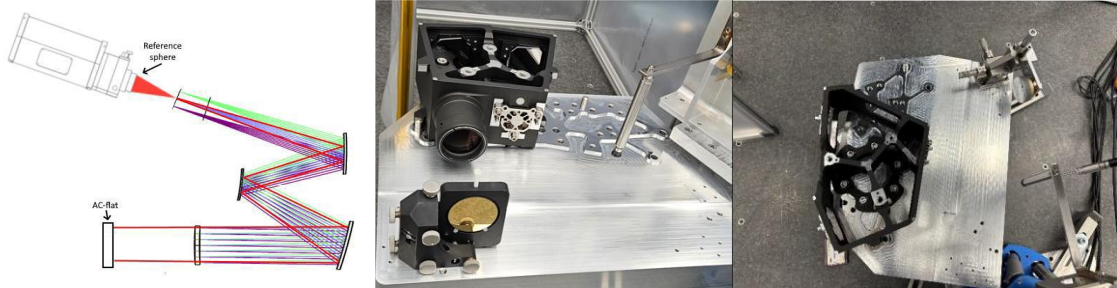


Figure 3-2: test configurations for FEO and BEO modules alignment and performance verification in standalone configuration

In terms of image quality and wavefront error, a specific scrutiny was placed on the vignetting over the beam path. Indeed, the mechanical design of the module driven to pass vibration requirements, forced to tailor very sharply the mechanical structure around the beam. One of the main goals for the alignment was to ensure vignetting avoidance, with a proper definition of the LOS of each module while still achieving adequate optical performances.

It was necessary to iterate on the modules alignment to prevent such vignetting over each module field of view. The iterations enabled a more accurate positioning metrology between mechanical datum surfaces and optical planes thanks to the test setup developed. It ensured a more direct identification of the nominal position each module required once integrated in the instrument optical benches.

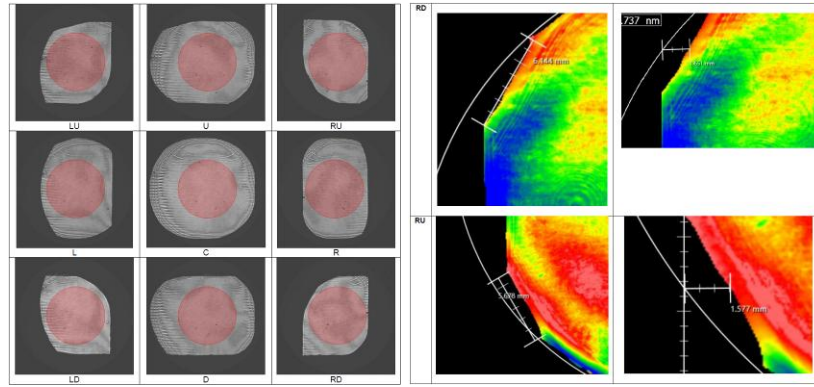


Figure 3-3: Illustration of the beam clearance wrt structure in the NIR BEO modules at several FOV and vignetting observed in a FEO at the beginning of the alignment.

For the UV channel, the alignment of the mirrors proved more challenging. The deposited coating is blocking VIS light reducing the capability to inspect optically the performances during alignment by typical 632nm interferometric measurements. A two-step approach was then defined to pre-align the mirrors in the mechanical module prior to coating, supported by a demonstration of the repeatability of the process to position each mirror nominally.

Table 3-1: MTF of the UV BEO prior mirrors to coating during pre-alignment rehearsal

FOV	MTF 0° @23.48lp/mm	MTF 90° @23.48lp/mm	Specification @23.48lp/mm
c	77 %	79 %	72 %
r	77 %	73 %	72 %
l	75 %	76 %	72 %
u	77 %	71 %	72 %
d	78 %	76 %	72 %
ru	72 %	68 %	65 %
lu	75 %	73 %	65 %
rd	76 %	75 %	65 %
ld	75 %	73 %	65 %

The intention to rely on nominal alignment, even after coating, by replacing mirrors without measurements was challenged by the inspection of each mirror after coating. After coating and heat treatment stabilization significant modification of WFE on all mirrors coated with black and grey coatings was observed. The quality of the interferogram measured on each mirror also reduced possibility to predict accurately how to reposition each mirror.

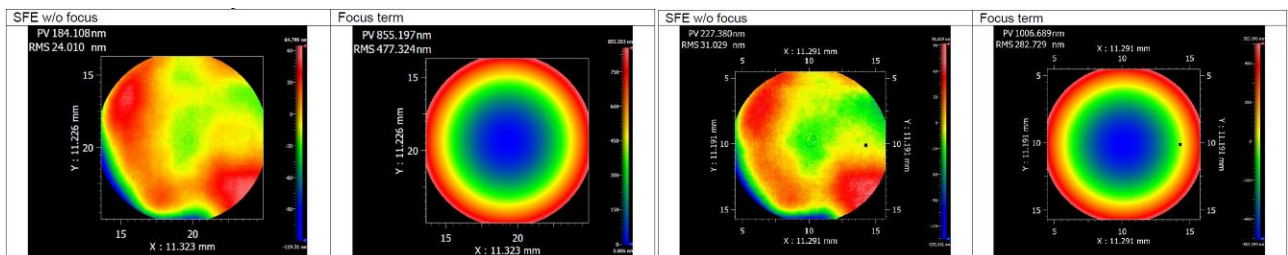


Figure 3-4: WFE before coating and after coating + stabilization treatment on UV STO M2 mirror

On the three-mirror back end optic module generating the image behind the FPIs, it was decided to reintegrate nominally the mirrors on the mechanical structure. The position of the BEO module itself would have then to be confirmed on the instrument optical bench during the alignment of the UV channel.

For the mirrors of the stellar optical path, the measurements could be used to adapt the assembly of the mirrors on their mounts and to provide additional inputs for the alignment of each unique mirror in the optical bench.

AOTFs for VIS and NIR channels

The development of the VIS and NIR AOTF was made under the responsibility of Gooch and Housego UK with, for the mechanical part, a design from OIP. Part of the development was reported in [3]. Multiple trial and steps by step development activities were required at G&H to enable the production of large AOTF modules from tellurium dioxide crystals. Multiple crystals were required to be developed as the polishing process of the surfaces, the cutting approach of the crystals was for a part, manual, leading to multiple mishaps and damaged cells. Once finalized the AOTF crystals were integrated with the housing mechanics by OIP team at Gooch and Housego premises and the crystal transducer/PCB electrical wire bonding and impedance matching was done by G&H personnel. The further mechanical integration and packing in external housing was done again by OIP AIV team.

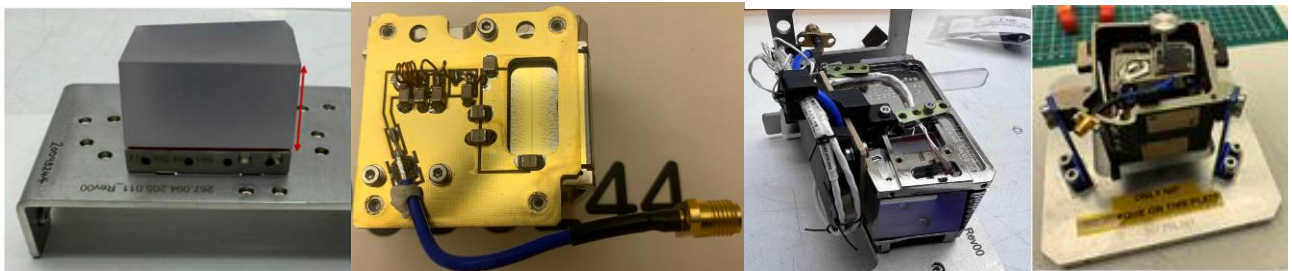


Figure 3-5: Various steps of integration of AOTF modules

Testing and verification of the VIS and NIR AOTF FM assemblies was done at Centre spatial de Liège. The fitting and alignment of the front and back polarizers was ensured to enable optimized light throughput and a full characterization of the performances in temperature was performed using the test setup described in Figure 3-6.

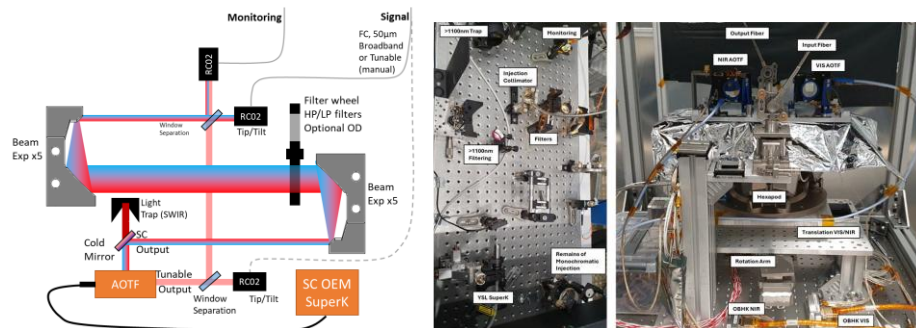


Figure 3-6: Overview of the test setup for AOTF calibration

The developed test setup also enables a full characterization of the RF frequency to wavelength response in temperature over the full wavelength range of operation for each AOTF as well as the angular distribution of the diffraction orders. A full angular and spatial mapping of the diffraction efficiency was also characterized for each module enabling to confirm the radiometric and geometric model of the AOTF. Identification of spatial signatures of the Schaeffer Bergman dispersion pattern was done enabling to get a better understanding of the needed spatial to spectral straylight calibration at instrument level.

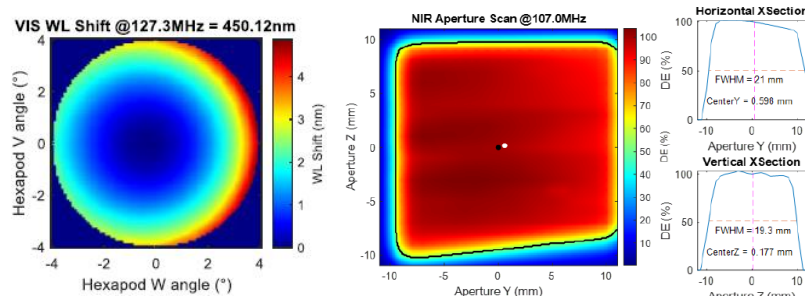


Figure 3-7: Example of the angular spectral distribution wrt AOI in VIS AOTF and spatial diffraction map of the NIR AOTF

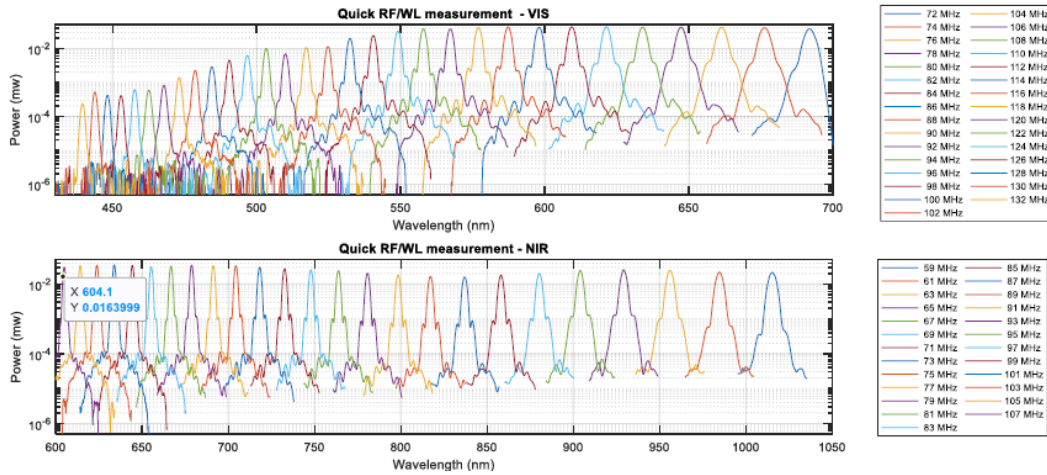


Figure 3-8: Spectral response function characterization of the VIS and NIR AOTF assemblies

Once calibrated, the AOTFs were tested together with the control electronics to validate the temperature correction algorithms. These algorithms compensate for the temperature-driven acoustic effects and their influence on the selected wavelength for a given RF frequency. Different types of correction algorithms were tested based on the calibration data received from TVAC tests. It was finally possible to demonstrate that the correction has an excellent impact on the wavelength stability which can be reached and that all correction methods are compliant to the spectral accuracy requirement over 1-10 and 3600s

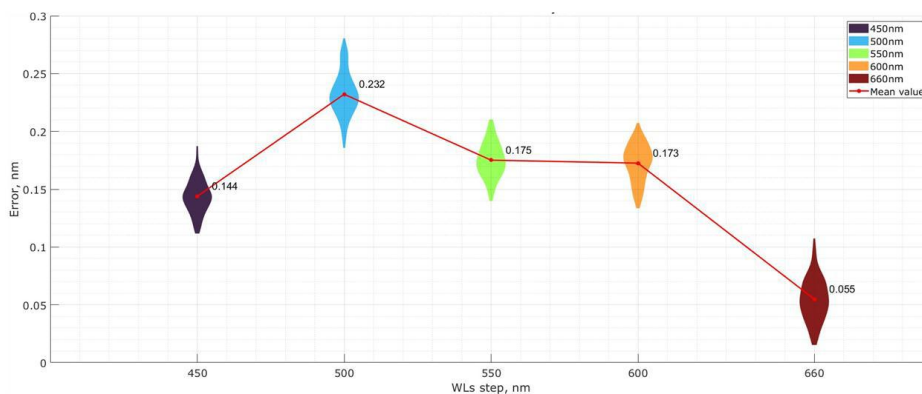


Figure 3-9: Spectral MPE at various WL (1nm MPE spec)for the VIS AOTF

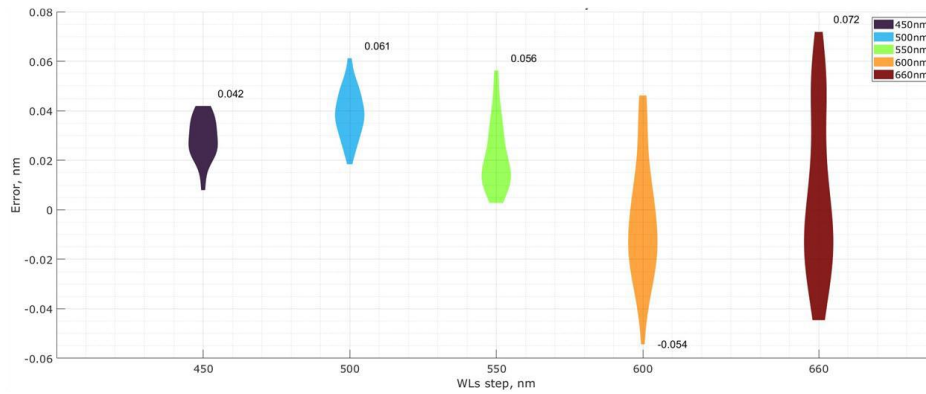


Figure 3-10: Spectral PDE at various WL (1nm MPE spec)

FPI assembly integration and tests

The design, development, and AIV of the FPI assembly was done by VTT Finland which developed a special expertise and tooling for the ALTIUS activity.

The selection of mirrors for the Fabry-Pérot interferometers (FPIs) was a lengthy and challenging process involving multiple manufacturing and characterisation stages. The process began with the characterisation of the polished fused-silica wafers before electrode fabrication, dicing and optical coating. Since each wafer produced multiple future upper and lower cavity mirrors (three pairs), the measured surface maps were used to evaluate many possible mirror combinations. The objective was to identify mirror pairs that would minimise cavity-shape errors and provide the most uniform gap distribution across the clear aperture. Once the optimum mirror pairings had been identified, the wafers underwent electrode processing, dicing, Bragg-mirror and anti-reflection coating deposition, followed by mirror characterisation. The selected mirror pairs were then used for the assembly of the individual FPI modules.

The selected upper and lower mirror pair are combined into a pre-assembled FPI unit and measured to evaluate the cavity-gap distribution across the aperture: The intention is to ensure for each FPI cavity the optimum distribution of the gap across the clear aperture. The pre-assembled FPI unit is integrated in a test setup where a fiber tip illuminates a small section of the clear aperture and the transmitted light is collected to a spectrum analyser. The optical surface of the pre-assembly is then scanned over a dense grid of measurement points providing a map of the gap between the two mirrors while removing global tilt errors, which will be calibrated for during FPI assembly.

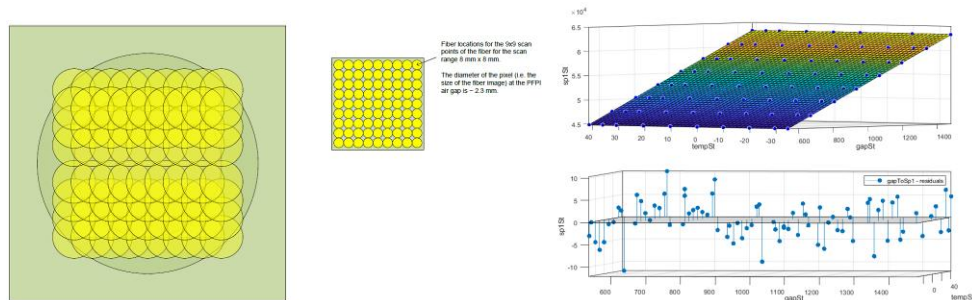


Figure 3-11: Illustration of the scanning principle allowing to evaluate the air gap a mirror-to-mirror orientations for a mirror pair.

The same process is repeated for each FPI cavity, so in total four mirror lots. There are four types of FPIs, each with a different Bragg mirror design wavelength. When used in a cascade this allows covering the whole operating wavelength range. The number of units represents a large number of combinations considering that test results could be still invalidated by cosmetic defects, coatings defects or electrodes depositions defects. The mirror pairs are secured and are assembled with the piezo electric stacks. The assembly process shall remove as much as possible global tilts of one mirror surface to another while the remaining tilts will be compensated for by activating the piezo actuators.

During the assembly and characterization campaign, the cavity-gap mapping technique described above was used to characterize the piezoelectric control response and to verify the quality of the assembled cavity. The measurement setup was subsequently integrated into a thermal chamber, allowing the FPI module to be characterized over its operational temperature range. These measurements confirmed that the assembly processes had not introduced additional deformations that could compromise the spectral performance of the cavity. The variation of the cavity gap with temperature for a representative FPI module is illustrated in the figure below.

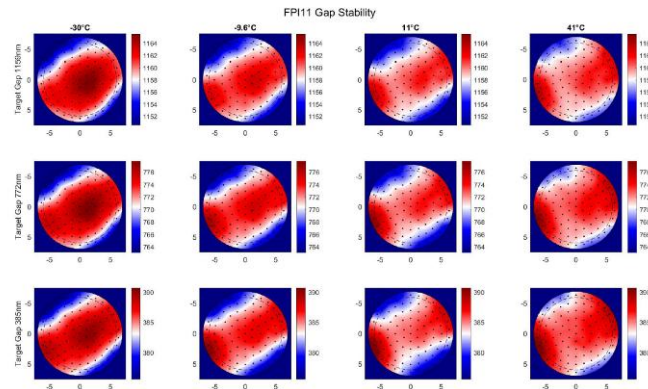


Figure 3-12: Temperature-driven map of a FPI module gap distribution over clear aperture for different nominal gap settings

The thermal-vacuum campaign enabled full calibration of the FPI operating states and characterization of the piezoelectric control parameters required for each cavity-gap setting.

The characterization campaign enabled the final selection of the flight FPI units, which were subsequently integrated into their mechanical housings. Accurate optical-to-mechanical referencing was then established through a combination of autocollimation verification and CMM metrology ensuring a high level of perpendicularity of the mirrors to the mechanics mounting interfaces. The alignment of the modules to mechanics is done in 3D space ensuring that the gluing layer between the fused silica substrate and the aluminum housing is even across the interface.

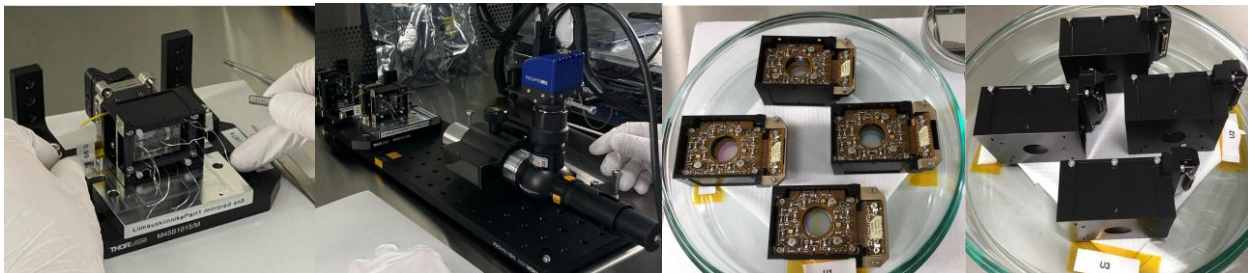


Figure 3-13: Various steps of integration of the FPI modules

After those critical steps the final driving electronics for the piezo actuators must be integrated and secured to the mechanics while the piezo wires must be soldered. The criticality here is the proximity of the operation from the optics and the importance of preventing contamination of UV optical components with fumes or solder fluxes.

The last step of integration at VTT is the coupling of each of the FPI modules into the FPI assembly. A common baseplate with flexures enabled the integration of the four modules together. The upside-down configuration was driven by the need of thermally insulating the FPI assembly from the optical bench. This ensures a very high decoupling when the FPI is wrapped in multi-layer insulation (MLI), enhancing spectral stability during operation. To prevent ghosting

effects, the relative orientation of the FPI units is critical. A hybrid alignment approach was therefore adopted, combining mechanical tolerances of the baseplate surfaces for one rotational degree of freedom with active alignment for the other, using an autocollimation reference to the mounting baseplate.

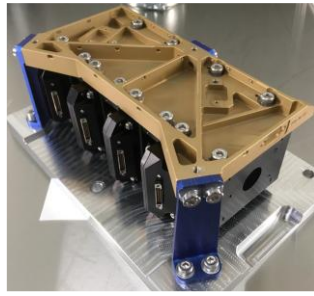


Figure 3-14: Final assembly FPI

Once assembly was completed, an extensive spectral and radiometric characterisation campaign was performed. The measurements confirmed that the flight FPI assembly met, and in some cases exceeded, the radiometric performance requirements. In addition, the measured spectral response showed good agreement with the predicted behaviour, validating both the optical design and the manufacturing approach.

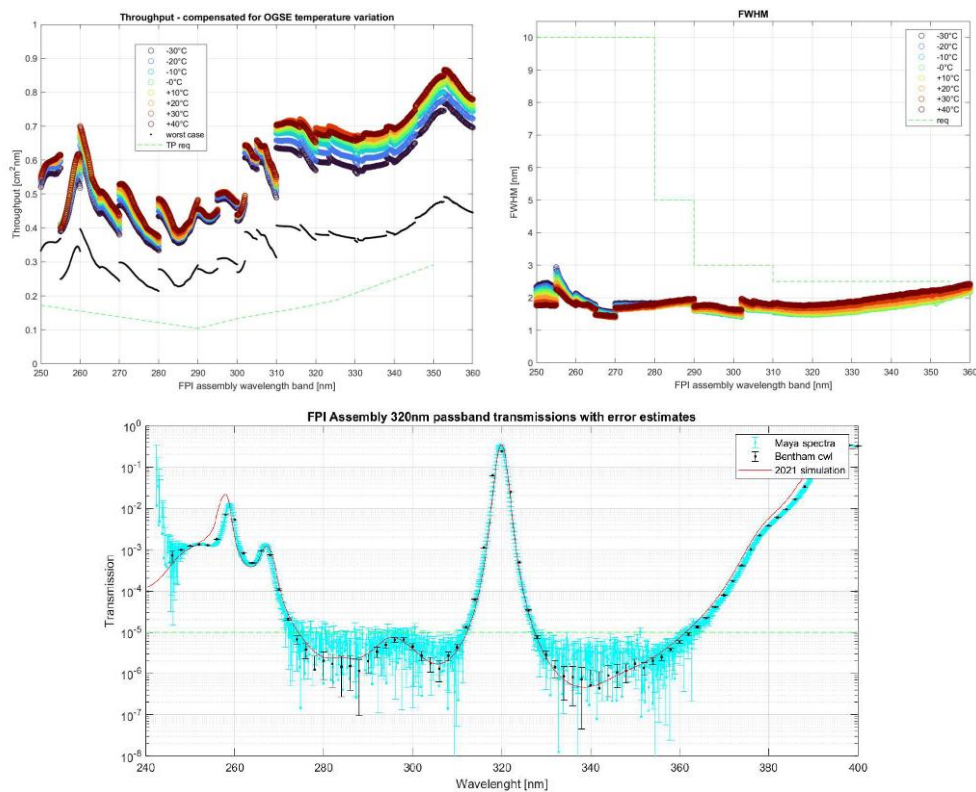


Figure 3-15: Throughput and FWHM of the FPI assembly across the wavelength range

4. CHANNELS INTEGRATION AND ALIGNMENT

The integration of the instrument has been started by the NIR channel. To this purpose the optical bench is positioned and referenced using optical reference cubes to the line of sight of the optical ground support equipment (OGSE). This

OGSE is composed of an integrating sphere illuminating a test pattern positioned at the focal plane of a 1585mm focal length collimator of 400 mm pupil aperture. The collimator illuminates a scanning mirror allowing it to stimulate different field points in azimuth and elevation within the FOV of the channel.

Integration of the optical elements in the optical bench is mainly based on mechanical tolerance and inherits the good accuracy of the optical modules manufacturing and the LOS measurements done at FEO and BEO level. The optical elements are integrated with a combination of shims sandwiched between datum surfaces and dowel pressed onto the optical bench. Their nominal position is defined, based on the metrology of the optical bench and optical subassemblies itself. A first pre-positioning alignment step was executed by adjusting the folding mirror presented in Figure 2-6 to ensure light goes without vignetting through the spectral filter in each channel. During this activity, a correction of the optical beam footprint position onto the AOTF clear aperture had to be executed based on the measured AOTF diffraction efficiency spatial map in Figure 3-7.

The second sequence of alignment is done through the integration and alignment of the focal plane. In this process, the adjustable section of the focal plane, containing the CMOS sensor, is integrated with a 6-DOF hexapod. This section shall be adjusted in 3D space on a static mounting interface hard mounted on the optical bench of the channel. The maintainability of the kinematic adjustment of the FPA is ensured by gluing the adjustable section to the hard mounted one using EC-2216 glue.

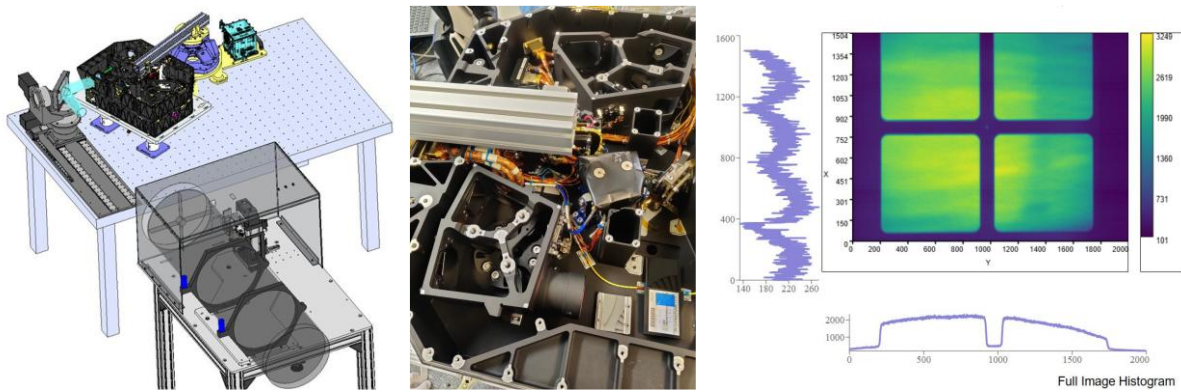


Figure 4-1: VIS/NIR optical bench in the alignment setup and first light onto the detector

To freeze each degree of freedom, an iterative alignment approach is executed consisting of the following steps while illuminating the channel with a pinhole pattern.

- The horizontal and vertical positions of the sensors are frozen based on the identification of the detector center pixel at the reference axis materialized by the OGSE and bench reference cube.
- The pitch and yaw of the sensor is referenced based on mechanical tolerance and cannot be significantly modified due to ghosting effects. It is then kept nominal to start the alignment.
- The detector roll is initially set by simple water levelling of the mechanics
- A first through focus scans with a nominal wavelength set in the middle of the range of channel operation is executed. The on axis one allows to identify a zone of optimum focus.
- The execution of the through focus at several key points of the FOV enables to identify detector roll and correct for it.

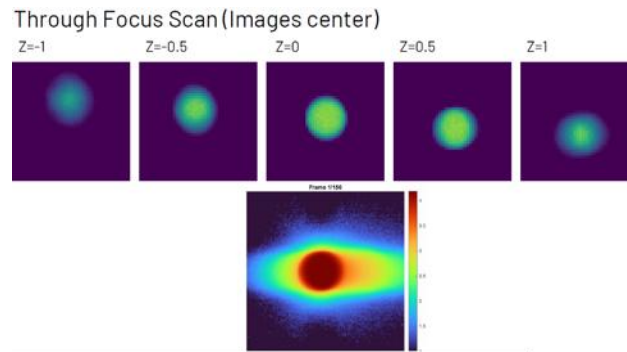


Figure 4-2: Rough through focus scan for VIS channel alignment

The focus scan is then executed on a narrower scanning region, close from identified local minimum, using a denser step and smaller pinhole test patterns. This allows to gradually improve the adjustment of the rotations and focus position over the full sensor (edges center and mid-range). Once the adjustment is considered complete line spread function (LSF) measurements are performed scanning a slit pattern of $1/10^{\text{th}}$ of a pixel width through several pixels with small scanning steps. Scanning is executed using a vertical and horizontal slit to characterize the LSF in the two imaging directions. The LSF data is acquired at three wavelengths within the range, 450-550-650nm for the VIS, 600-820-1020nm for the NIR to ensure the optical performances are maintained throughout the full operational spectral range.

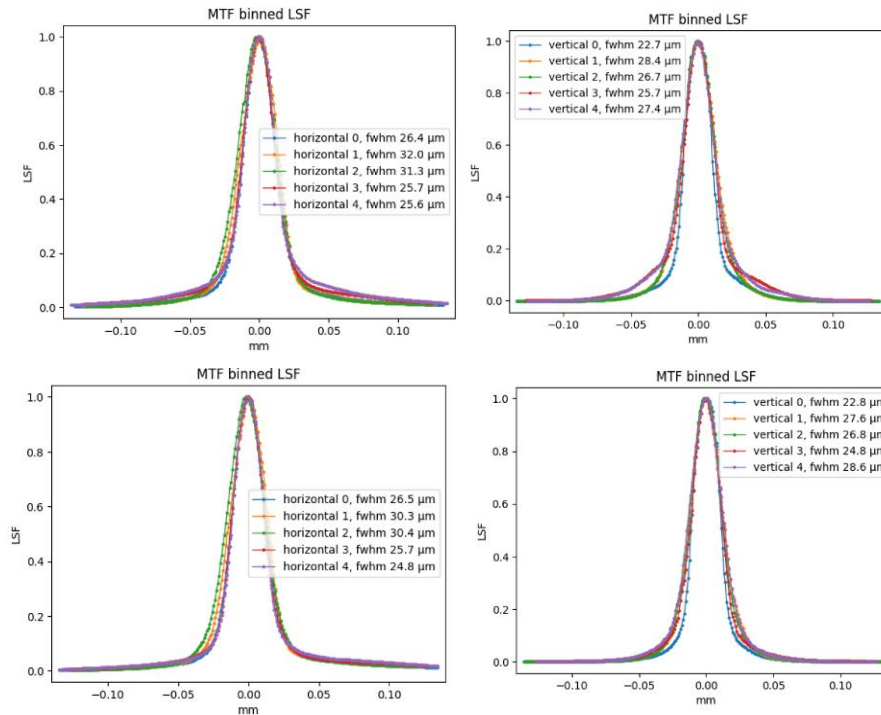


Figure 4-3: LSF measurement at best focus in horizontal and vertical at 450nm (top) and 650nm (bottom) in the VIS channel at best focus

In the VIS channel, LSF FMHM expectations are met and the derived MTF is in line with the project needs. In the NIR channel, a strong reduction of performances below expectations was observed, in particular at high wavelength.

During the alignment iterative process, a Schaefer-Bergmann pattern was observed with a characteristic dispersion of the spot in the azimuth plane, corresponding to the plane of diffraction of the AOTF. The relative amplitude of this pattern

with respect to the LSF peak intensity was observed to increase with the increase of the wavelength. It unfortunately resulted in a reduction of the achievable MTF below the theoretical prediction with a clear performance asymmetry in azimuth in comparison with the elevation.

The LSF in the NIR range shown in Figure 4-4 illustrate a large extension of the LFS foot, worsening in wavelength, while LSF peak and FWHM remains quite stable over the wavelength range. All field points tested are impacted in a similar way by this degradation. As the optical bench is oriented at 90° to image the atmosphere this generates a degradation of the imaging quality on the vertical of the atmosphere. The impact of this effect on the end-to-end performances is nevertheless mitigated as the VIS and NIR optical designs have been conceived to produce a spatial oversampling of the required atmosphere sampling distance projected at the tangent altitude of the earth.

As a consequence, after discussion with Redwire and ESA and verification of the mission level requirement achievements, it was decided to carry on with the gluing and securing of the FPAs for both VIS and NIR channels. The performances were maintained after the release of the hexapod tooling and final verification of performances.

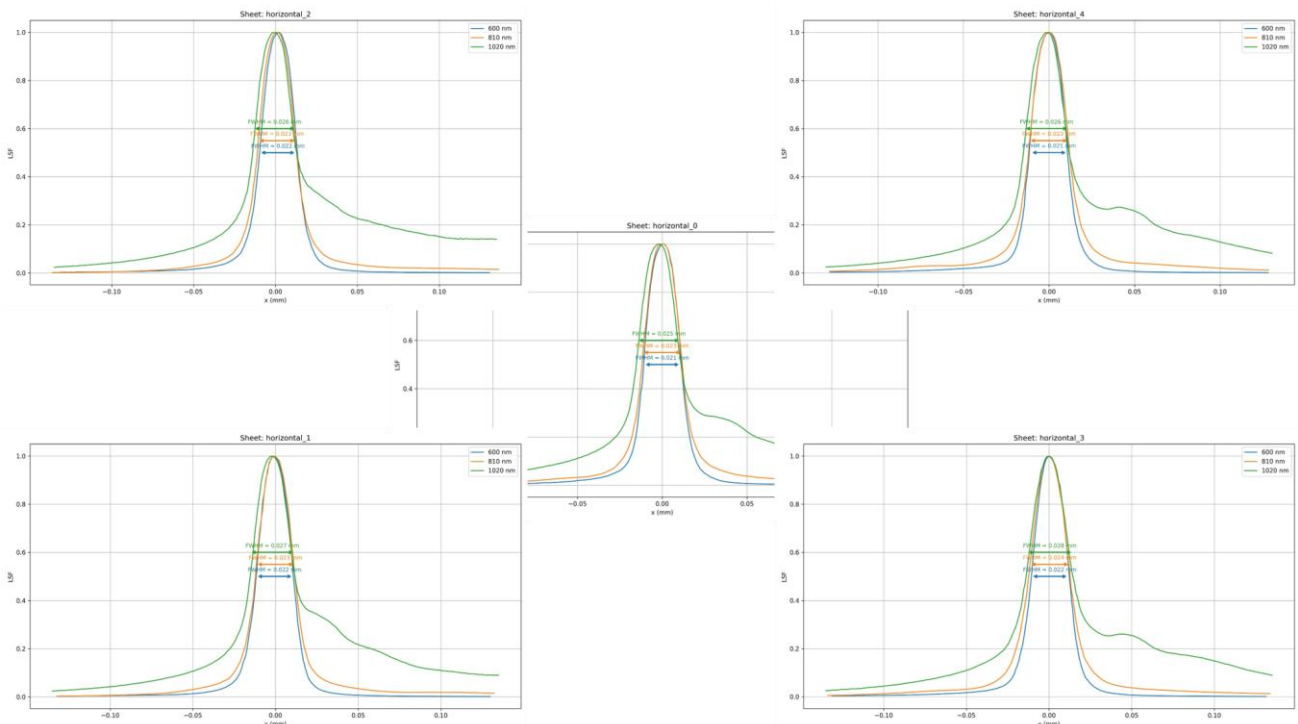


Figure 4-4: LSF of the aligned NIR channel over the wavelength range (green: 1020nm, orange: 820nm blue: 650nm) on axis and at the edges of the NIR channel FOV during horizontal slit scan.

The alignment of the UV channel follows a similar approach to the one of the VIS and NIR using the same OGSE configuration. It is done in two stages, with first, the FPA integration for bright limb optical path and the alignment of the STO magnifying optics is done in a second instance.

In bright limb path, the coating effects observed on the WFE of each BEO module mirrors introduced an additional uncertainty in the position of the BEO. The alignment of the FPA was starting using the nominal positioning BEO as planned by the CAD model. A provision for further alignment was kept. Fortunately, the detector alignment proved to be acceptable without additional BEO adjustments. MTF revealed to be above the requirement for all fields after FPA alignment only, as can be seen in Figure 4-5.

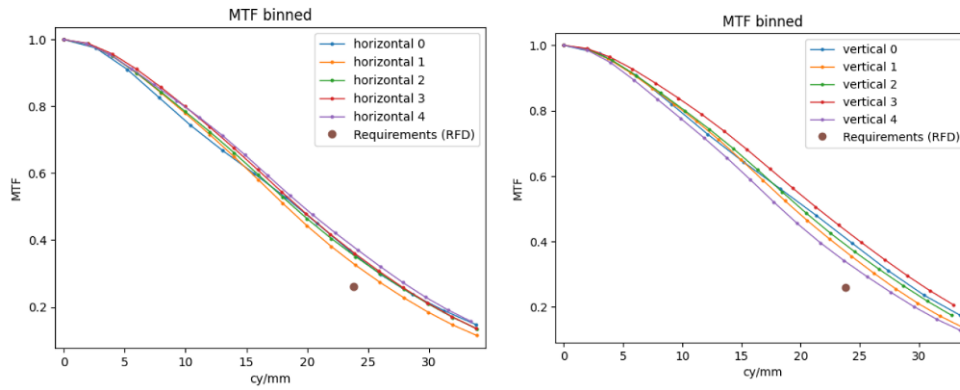


Figure 4-5: As build MTF performances of the UV channel bright limb path

Nevertheless, the alignment of the UV bright limb path also revealed the presence of a ghost in the FOV. After investigation identified as originating from the Fabry-Perot stack. This ghost cannot be reduced anymore without tilting differently each FPI making void all the spectral and radiometric calibration activities done on the FPI assembly.

An analysis of the situation has concluded that a further knowledge of the ghost behavior will have to be gathered during the instrument calibration campaign.

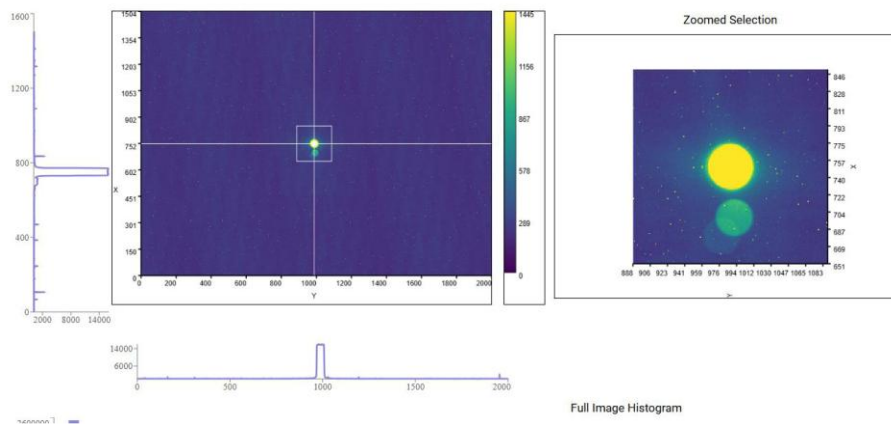


Figure 4-6: Illustration of the observed ghost in the UV channel of the instrument due to FPI assembly

The integration of the STO path was, for its part, quite perturbed by the WFE impact from the coating. As build WFE of the mirrors were projected to generate a significant drop of the encircled energy on one pixel, being the main performance indicator. An end-to-end drop from 80% to 46% energy on one pixel including build and in-flight effects was anticipated. The alignment, which was initially planned mainly acting on the second mirror of the STO path for focus and third mirror for LOS adjustment was extended to a full readjustment of the nominal position of each mirror. An additional adjustment of the M1 mirror with limited influence on the end-to-end encircled energy on one pixel was also attempted.

Best and final figure reached were despite all efforts in the vicinity of 35% encircled energy including predicted as build and in-flight effects.

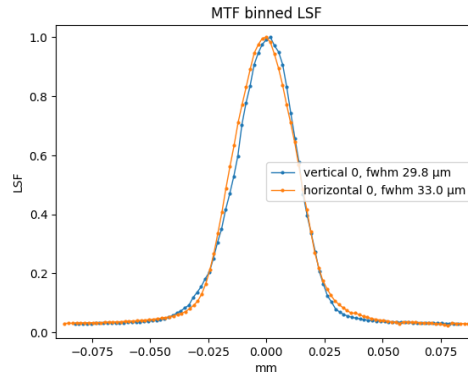


Figure 4-7: LSF obtained on the stellar optical path of the UV channel after alignment of the mirrors at 350nm

Fortunately, this reduction of the encircled energy is mitigated by the improvement of the spectral filter throughput, coating reflectivity compensating for radiometric losses, and by the possibility of binning of multiple pixels in the stellar occultation. These effects resulted in a higher than anticipated signal-to-noise ratio for most observed star in the UV range which is limiting the impact of the performance decrease on the mission goals.

5. ACTIVITIES UNTIL LAUNCH

The three optical benches of the instrument are now completely integrated aligned and ready. The next step is the assembly of the VIS/NIR and UV benches together to form the full optical unit. This bench marriage will be completed by the integration of the mounting flexures, star trackers and front straylight baffles. The assembled optical unit will be then repositioned in front of the OGSE where the line of sight of each channel will be co-aligned to each other. The co-alignment is done by adjusting periscope mirrors positioned at the entrance of each optical bench (see Figure 2-2 and Figure 2-6). This last step will enable a precise adjustment of each line of sight.

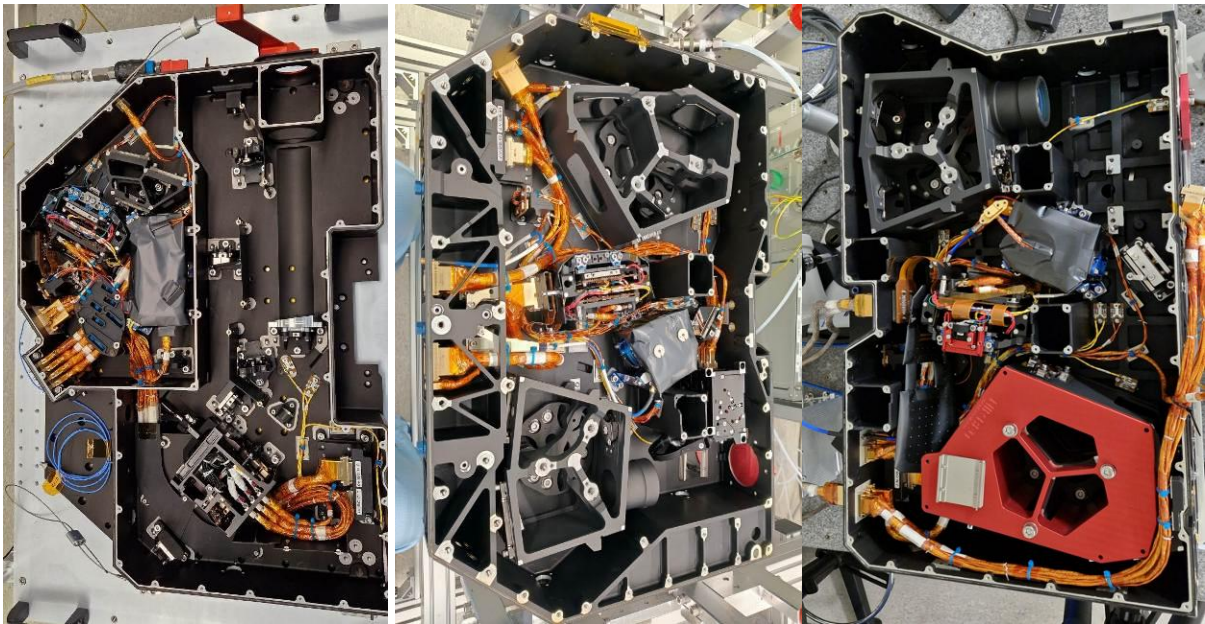


Figure 5-1: Fully integrated UV; VIS and NIR channels

The preparation of the OU is done in parallel with the testing and verification work for each FM PCBs composing the CCU units. Integration and verification and environmental qualification of each CCU stand alone is a pre-requisite to validate suitability of the electronics flight hardware and support optical verifications to be executed on the full

instrument. Due to timing constraints after the co-alignment, a very quick set of performance tests is foreseen in September - October 2026 to better explore the instrument's optical behavior. Indeed, additional verification is desirable prior to the calibration campaign, as no qualification model was available to validate most of the optical or spectral models built so far. These measurements will support the consolidation of the calibration campaign and OGSE developed [6] to support geometric, radiometric spectral and straylight testing activities. This preparation is planned to be completed while the instrument will go through its environmental test campaign. and calibration campaign. This last sequence is foreseen beginning of 2027 before integration on the satellite second quarter 2027.

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