

OPTICAL ALIGNMENT PLAN FOR COMPACT HIGH-RESOLUTION SPECTROMETERS INSIDE THE ANSER-AT MISSION

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ABSTRACT

The optical alignment plan for the fractionated spectrometer to be distributed in a cluster of four CubeSats, each of them working in a different spectral range, as part of the ANSER-AT mission is presented along with the strategy adopted for the complete and reduced functional tests and performance verification. The payload of each CubeSat is composed of two optical systems: a telescope (TEL) and a spectrometer (SP). The TEL unit is the same for all the satellites while the SPs differ and are optimized for each spectral operating range. The alignment has been divided into different steps combining image quality and spectral characterization techniques according to the tolerance analysis and the resulting compensators. Complete performance tests consist of verifying the spectral and spatial resolution, digital SNR, straylight, spectral range, radiometric model validation and polarization degree. Additionally, reduced functional tests will consist of the measurement of the position and size of the spectrometer object image -a slit- projected on the detector.

Keywords: Optical alignment plan, fractionated spectrometer, telescope, performance verification

1. INTRODUCTION

ANSER AT (Advanced Nanosatellite Systems for Earth-observation Research – ATmosphere) is a mission part of the INTA's SmallSat Constellations Program (ANSER) and it is dedicated to the study of the chemical composition of the Earth's Atmosphere. The mission is based on the development of a fractionated spectrometer distributed in a cluster of four CubeSats flying in formation (6U for each CubeSat). The payload of each CubeSat is designed to work in a different spectral range in order to measure several atmospheric compounds of chemical-climatic interest under different scenarios and with different scientific objectives. The four spectral ranges are 320-355nm (UV) to assess the ozone layer recovery process, 420-455nm (VIS) for the measurement of nitrogen dioxide, 756-773nm (NIR) for measuring the oxygen column and 1550-1680nm (SWIR) for the measurement of carbon dioxide [1].

The payload of each CubeSat is composed of two optical systems: a telescope (TEL) and a spectrometer (SP) and, additionally, UV and VIS instruments include a small optical subsystem to provide in-flight calibration (Reference Module). The TEL unit is the same for all the satellites while the SPs differ and are optimized for each spectral operating range. The telescope collects the spectral flux of the scene and projects it into the input slit of each spectrometer. Then, the spectrometer disperses the signal coming from the slit and collects it on a photo-detector. The slit projects on the ground a rectangular area of 7Km in the across-track direction and the information corresponding to an area of 7x7Km will be obtained accumulating individual acquisitions.

The alignment of the optical subsystems (TEL and SP) has been divided into different steps combining several procedures for image quality measurement such as MTF or interferometric measurements along with the appropriate techniques for spectral characterization. For the telescope alignment, as it was designed to be the same for all spectral ranges, interferometric techniques are employed as it presents high optical quality for the interferometer working wavelength. However, the spectrometers alignment is performed illuminating with the adequate wavelength in each case by using a broad lamp and interferential filters.

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2. PAYLOAD GENERAL DESCRIPTION

The ANSER AT instrument is composed of a telescope for collecting energy of the scene and a spectrometer that ensures spectral and spatial resolution requirements focusing the collected energy on the Focal Plane Unit.

The telescope subsystem, which is the same for the four CubeSats, is based on a catadioptric configuration with a focal length of 281mm and an aperture of 80mm due to the volume limitations imposed by the CubeSat standard [2]. It is based on a Schmidt-Cassegrain configuration with a parabolic primary mirror and a hyperbolic secondary mirror. It also includes a lens barrel (two conic lenses) to cover the wide angular field [3] indicated by the long side of the entrance slit to the spectrometer which size is defined by the spatial and spectral resolution required for each spectrometer. The entrance slit assembly is placed at the telescope focal plane providing the mechanical interface between the telescope and the spectrometer.

The four spectrometers are optimized for each spectral range, but all of them follow the same scheme: the light incoming through the entrance slit is collimated, dispersed by a reflective grating and then, a collector subsystem focus the light onto the detector unit.

The collimator subsystem consists of a barrel of lenses that collects the light from the telescope and collimates it to reach the diffractive element. The focal length of this subsystem is limited by volume restrictions and according to the diffraction grating aperture. The diffraction grating assembly, that is composed by the grating and its mechanical structure, spectrally disperses the incident collimated light and is one of the most important elements of the spectrometer. It has been selected for each spectral range considering the minimum lines per millimeter need to achieve the required spectral resolution. The collector subsystem, consisting of a lens barrel, collects the dispersed energy and focuses it onto the detector. The collector focal length is conditioned by the linear dispersion, resolution and sampling requirements.

Additional optical elements are included in the instrument to meet the mission requirements: two folding mirrors to compact and ensure that the complete instrument satisfies volume constraints and an interferential filter for selecting the spectral range. Last, it is important to reduce the polarization degree of the light to achieve the required radiometric accuracy [4]. For that purpose, two scramblers are included to convert any polarized beam into a pseudo-random polarized beam by introducing a different phase retardation along its aperture [5].

Figure 1 shows the optical elements conforming the instrument in the VIS spectral range and the corresponding optomechanical design. For other spectral ranges, the collimator, collector and grating have some differences in lenses description or grating parameters, but the mechanical configuration is the same for all instruments.

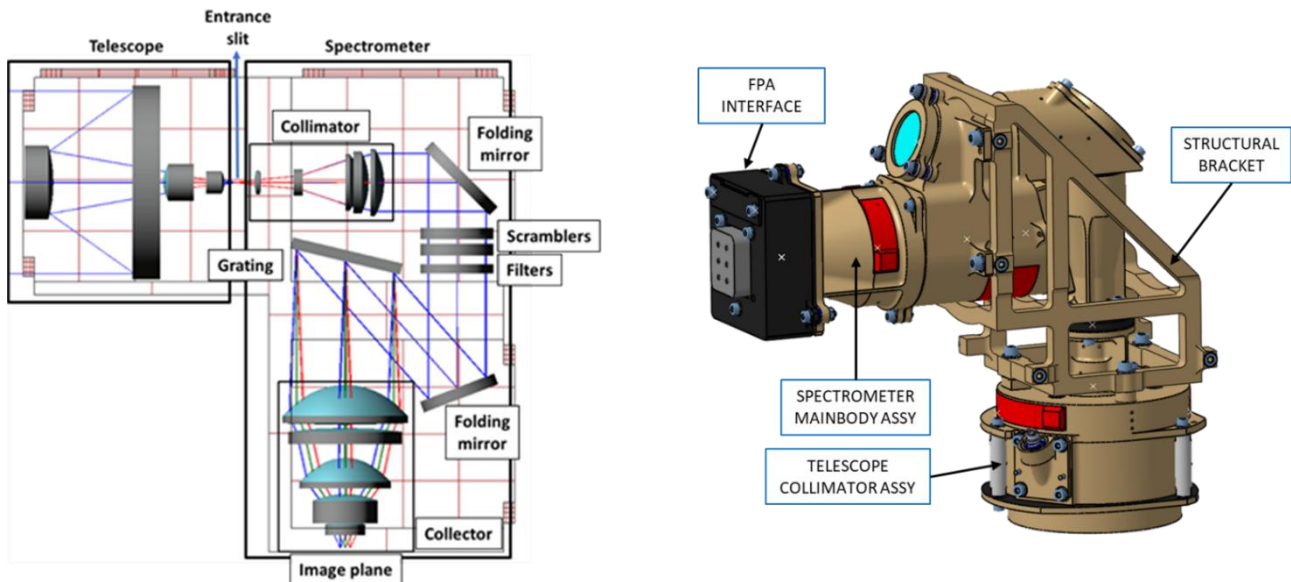


Figure 1. ANSER AT optical layout (VIS) located in the 3U CubeSat structure (left) and the payload optomechanical design.

3. INTEGRATION FLOW

The proposed main ANSER-AT payload assembly, integration and verification flow is as follows:

- Telescope mirrors and lens barrel integration, alignment and optical quality verification.
- Slit integration at the telescope focal plane.
- Collimator subsystem integration together with the telescope, alignment and optical verification.
- Spectrometer main body integration, which includes filters, scramblers, folding mirrors, grating and collector subassemblies.
- Focal Plane Assembly (FPA) integration, alignment and optical verification.
- Optical performance verification.

To facilitate the instrument integration and alignment, the model has been divided into two parts, attached to a rigid external frame (structural bracket) that also interfaces with the CubeSat structure. Therefore, the instrument is composed of the following mechanical subassemblies: 1) the structural bracket supporting all the components, 2) telescope and collimator assembly and 3) spectrometer and FPA (Figure 2).

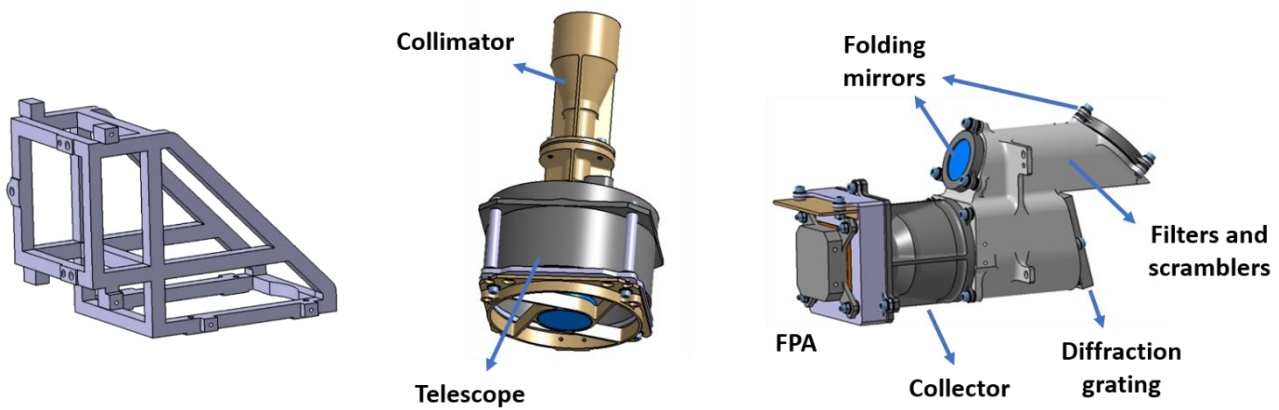


Figure 2. Structural bracket (left), telescope and collimator assembly (middle) and spectrometer and FPA (right).

4. INTEGRATION, ALIGNMENT AND VERIFICATION PLAN

The process of integration and alignment of the instrument is divided in different steps to measure optical performance at each step and ensure the instrument as a whole fulfills requirements.

4.1. Previous activities

Prior to starting with the integration of the instrument, the reception and inspection of all parts have to be performed to verify that every part is present and fulfills the specifications. Then, each optical element has to be assembled, this is, the mirror on their mounts and the lenses on their barrels.

Once mounted on their barrels, the optical quality of collimator and collector subsystems is verified through the measurement of the MTF. These measurements are performed in an optical test bench consisting on a light source (adequate for each spectral range) with the object to be projected (a slit whose width is adapted as a function of lens barrel focal length), a collimator (off-axis parabolic mirror) and a detector (again, adequate for each spectral range). Additionally, the barrel under test is placed on a mechanical stage that allows tip&tilt adjustment for aligning the barrel. The procedure is to obtain the values of the MTF at the Nyquist frequency of the collimator and collector subsystems for each spectrometer and for the on-axis field. The next Table 1 shows the MTF values provided by the design.

Table 1. MTF at Nyquist frequency for each collimator and collector subsystem.

Spectral range	Nyquist frequency (cy/mm)	Collimator MTF	Collector MTF
UV	35.7	0.945	0.971
VIS	35.7	0.930	0.958
nIR	35.7	0.878	0.931
SWIR	33.3	0.738	0.834

4.2. Telescope assembly and alignment

The telescope subsystem includes primary (M1) and secondary (M2) mirrors on their mounts that are separated by Invar36 bars to ensure the best possible athermalization of the system. The M1 mounting acts as a baffle and the M2 mount has been designed with a spider to reduce aperture obscuration. Additionally, the lens barrel is attached to the back side of the M1 mount. The alignment of the lens barrel is assured by tolerances. The positioning of the lens barrel with respect to the telescope mirrors is defined by means of a reference surface in the M1 mount, the lenses barrel and its rotation is locked by a dowel pin and the assembly is fixed to the M1 mount by means of three M3 screws. All mechanical elements composing the telescope are presented in Figure 3.

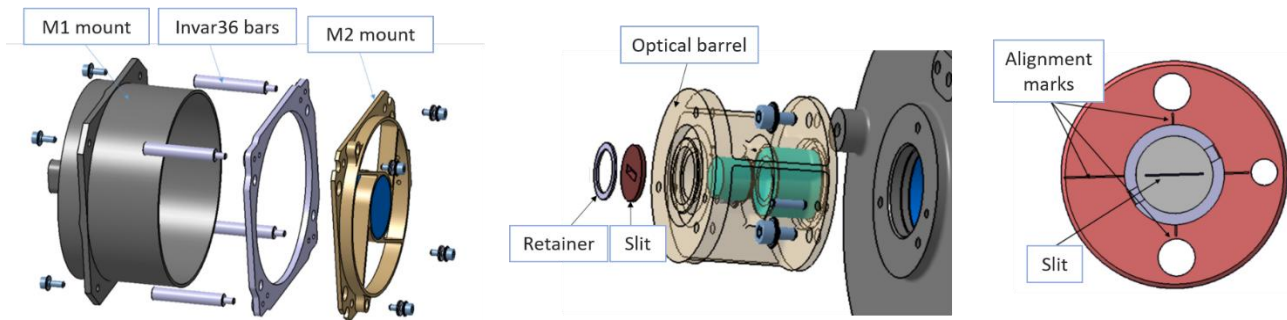


Figure 3. Primary and secondary mirrors assembly (left), lens barrel assembly (middle) and slit assembly (right).

At the front of the lens barrel the slit is placed, at the telescope focal plane. The slit is fixed by means of a screwed retainer. The tip&tilt slit position is met by mechanical manufacturing tolerances while the rotation angle of the slit is aligned with the mount mechanical references (alignment marks shown in Figure 3) using a microscope.

During the assembly of these elements, the optical alignment has to be performed and ensured at each step: M1 and M2 alignment, lens barrel alignment and positioning of the slit at the focal plane of the telescope. Both, the M1-M2 alignment and the alignment of the lens barrel are verified interferometrically and achieved by means of the compensators defined during tolerance analysis in accordance with the optomechanical design. These compensators are X, Y displacement of M2 to allow recovering optical quality and X, Y, Z displacements of the slit to assure that the slit matches the focal plane of the telescope (Z axis defined along the light path).

The full telescope is mounted on a hexapod (by means of the hexapod attachment shown in figure 4) that allows the alignment of the telescope with respect to the interferometer and the inspection of the whole field of view. The displacements of M2 are performed by means of the M2 alignment tool (Figure 4 left) while the displacements of the slit are provided by the slit alignment tool (Figure 4 right).

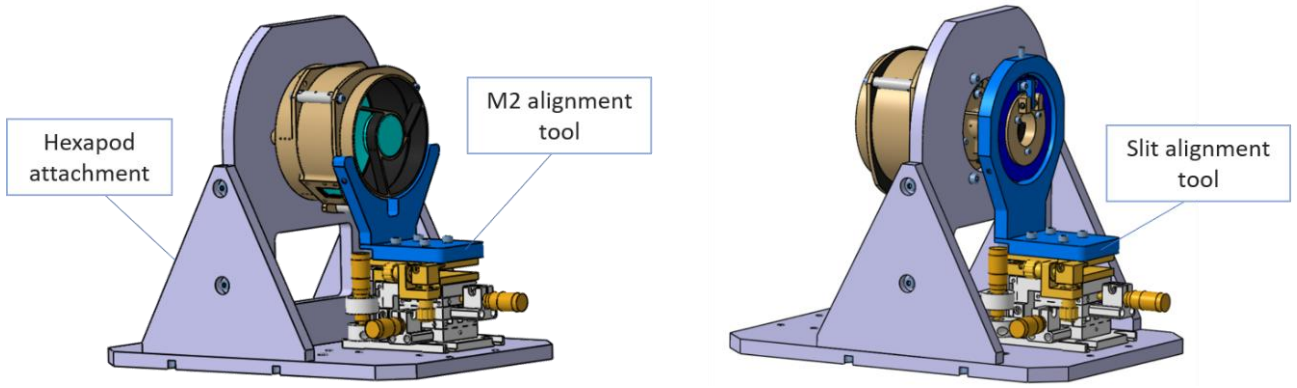


Figure 4. Telescope in the hexapod attachment with the M2 alignment tool (left) and with the slit alignment tool (right).

First, the primary mirror on its mount is placed on the hexapod attachment and aligned to the collimated beam coming from the interferometer and using the hexapod adjustments, decenters and tilt&tip. This alignment position sets the reference for the on-axis field of view. Then, the secondary mirror is positioned in the interferometer optical path and the double pass interferometric cavity is closed using a retro-sphere at the focal plane. The alignment between the mirrors is achieved when the wavefront error has an RMS (root mean square) on-axis better than 0.15λ ($\lambda=632.8\text{nm}$). For that purpose, the decenters of M2 are used as compensators. Next, the lens barrel is assembled, the double pass cavity is again closed with the retro-sphere and the compensators again actuated until the wavefront error has an RMS on-axis better than 0.26λ ($\lambda=632.8\text{nm}$). Last, the slit is positioned and adjusted by the measurement of the field of view of the telescope using the angular motion provided by the hexapod. The success criteria for this step are measuring a field of view that matches the design (it depends on each spectrometer) and symmetric with respect to the optical axis.

With this, the telescope is integrated and aligned, including the entrance slit of the spectrometer.

4.3. Collimator alignment

The first optical subsystem of the spectrometer is the collimator which consists of a lens barrel attached to the telescope's lens barrel by means of three M3 screws. The axial adjustment of the collimator, that is the compensator defined for this alignment, is adjusted by means of the collimator alignment tool (Figure 5 right) and materialized by a shim between the two barrels. All these elements are presented in Figure 5.

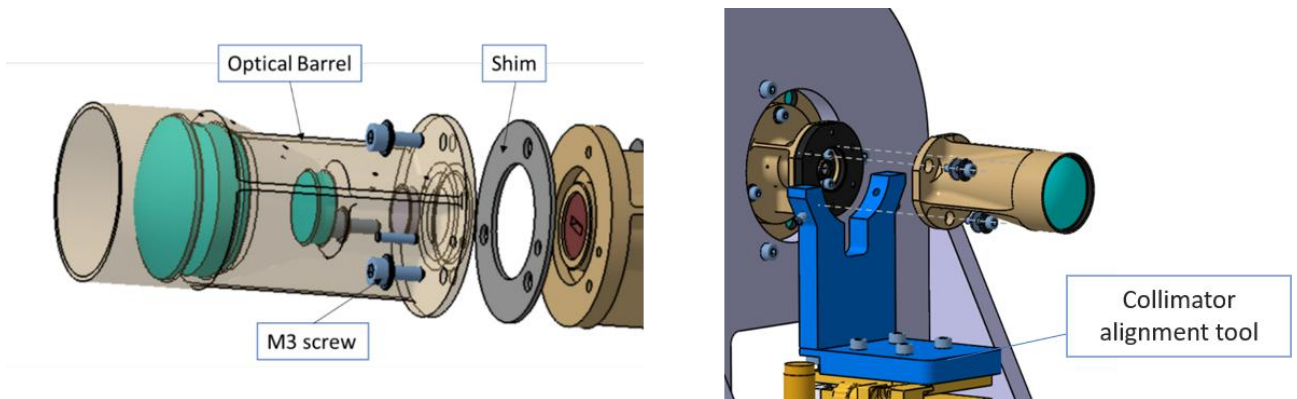


Figure 5. Collimator assembly (left) and collimator alignment tool (right).

It is important to note that the spectrometers work at different spectral ranges, but the alignment with respect to the telescope follows the same procedure for all collimators. The only difference is that the light source and the detector used for the alignment may need to be adapted to the specific spectral range. The proper alignment of the collimator is measured by means of the collimation degree and achieved by adjusting its axial position with respect to the focal plane of the telescope. For this measurement, the telescope is illuminated by a collimated beam at the adequate wavelength and an interferometric shear plate is positioned at the exit of the collimator. The position of the collimator is adjusted until the collimation degree is maximized.

4.4. Spectrometer assembly on main body

The spectrometer subassembly includes the spectrometer main body, the collector and the FPA. The spectrometer's main body is the interface for the folding mirrors and mounts, the interferential filter, the scramblers and the diffraction grating. The collector is attached to the spectrometer main body while the FPA is attached to the collector assembly (Figure 6).

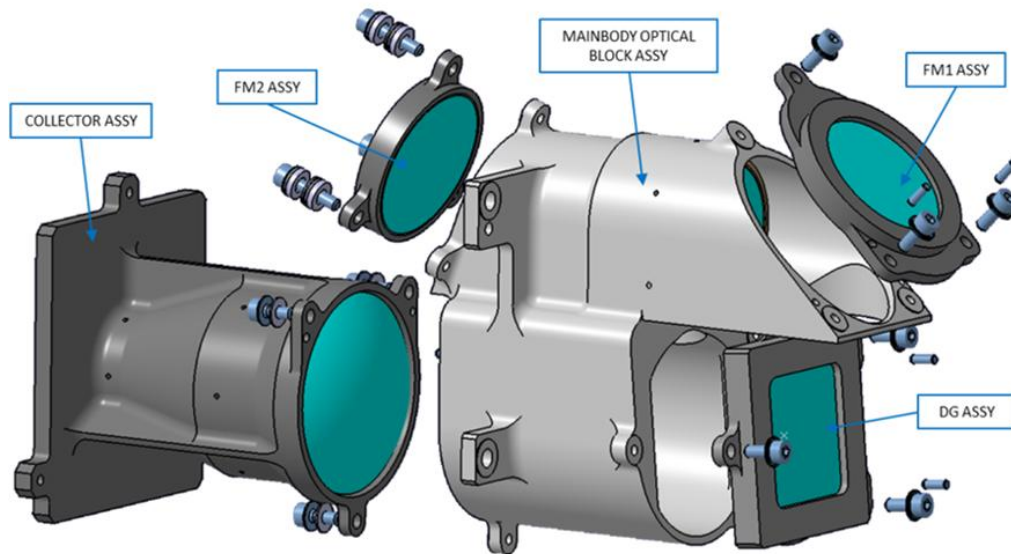


Figure 6. Spectrometer assembly.

The first step is to introduce in the main body the scrambler unit consisting of 2 depolarization wedges and their barrel (Figure 7 left). The integration and alignment of the scrambler unit is performed in a specific optical bench consisting of a laser, a lineal polarizer and a quarter waveplate [6]. This procedure consists of positioning the first scrambler in the mechanical structure, fixing that scrambler by means of the adhesive type RTV, positioning the second scrambler rotated 45° with respect to the first one and, once the polarization degree of the unit is verified, the second scrambler is fixed by means of the same adhesive. Finally, the scrambler unit is inserted in the main body. The measured depolarization degree must be better than 98%. Then, the interferential filter is also inserted in the spectrometer main body (Figure 7 right).

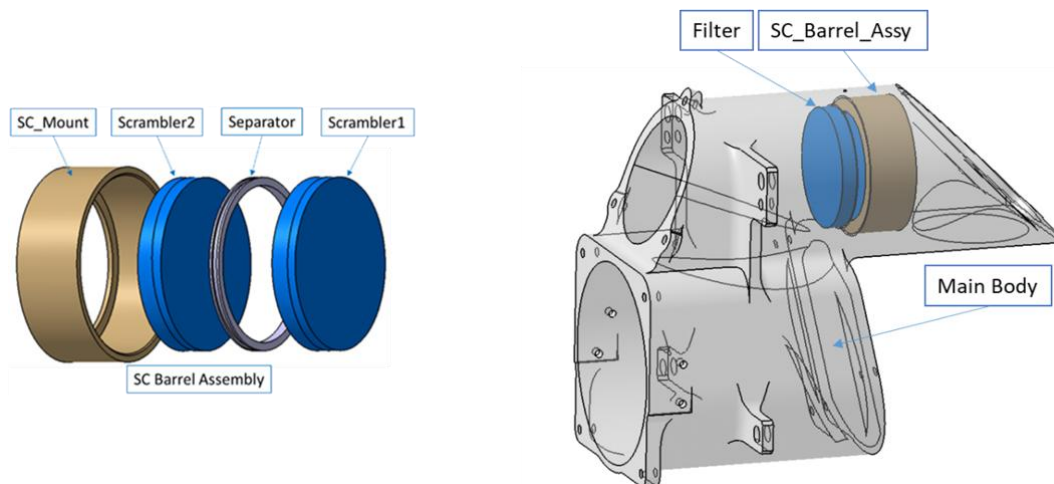


Figure 7. Scrambler unit (left) and the spectrometer main body (right).

The next step is to assemble the main body to the structural bracket. For that purpose, the structural bracket is attached to a mechanical element (spectrometer attachment) to fix the position of the bracket during the insertion of the main body. All the following operations are performed in this configuration (Figure 8).

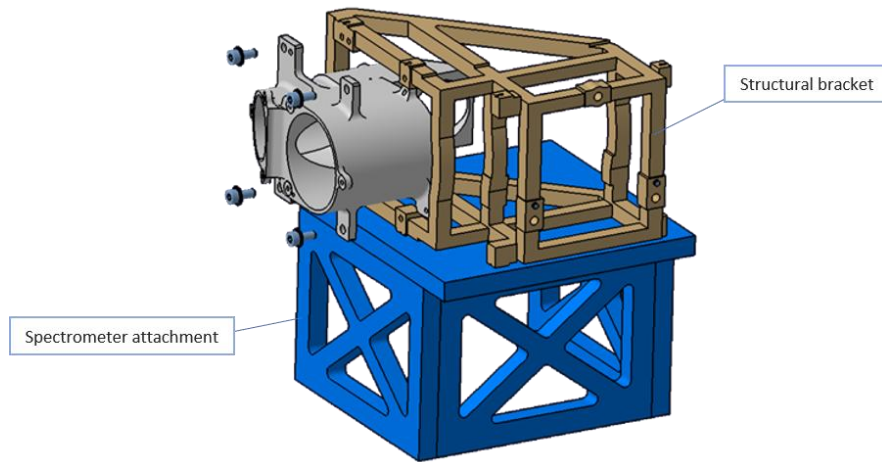


Figure 8. Structural bracket attached to the spectrometer attachment.

The last elements inserted in the main body are the diffraction grating and the folding mirrors. The grating assembly is a mount that holds the diffraction grating by means of three legs that are compound of M3 bolts and several shims to regulate the required height (Figure 9 left). The two folding mirror units (FM1 and FM2) are composed of a mount supported by three legs with M3 bolts and two pairs of conical/spherical washers (one at each side of the mount) for each leg (Figure 9 middle and right). The use of this layout of washers allows to minimize the appearance of bending moments when tightening the bolts once the adjustment has been completed. Additionally, the legs of FM2 include several shims to regulate the required height, as FM2 was defined as a compensator during tolerance analysis.

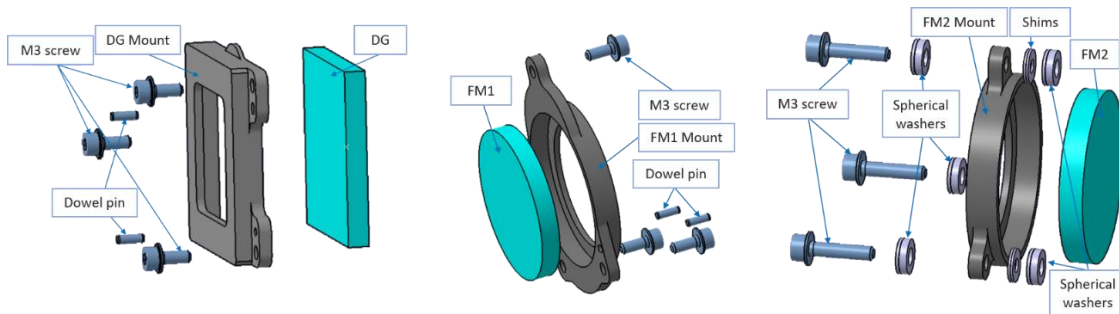


Figure 9. Diffraction grating assembly (left) and folding mirrors assemblies, FM1 (middle) and FM2 (right).

At this point, a first adjustment of the folding mirror FM2 (compensator) is performed to ensure that there is no vignetting at any element up to the exit of the main body, where the collector will be placed.

The last element to be attached to the spectrometer main body is the collector that is fixed by means of M3 screws and the required shims (Figure 10).

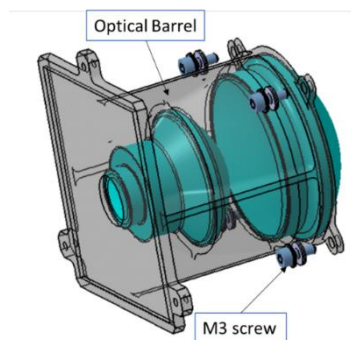


Figure 10. Collector assembly.

4.5. Telescope-spectrometer assembly

The structural bracket holding the main body is kept on the spectrometer attachment and the subsystem telescope + collimator is attached to the rest of the instrument through the structural bracket that holds everything together (Figure 11).

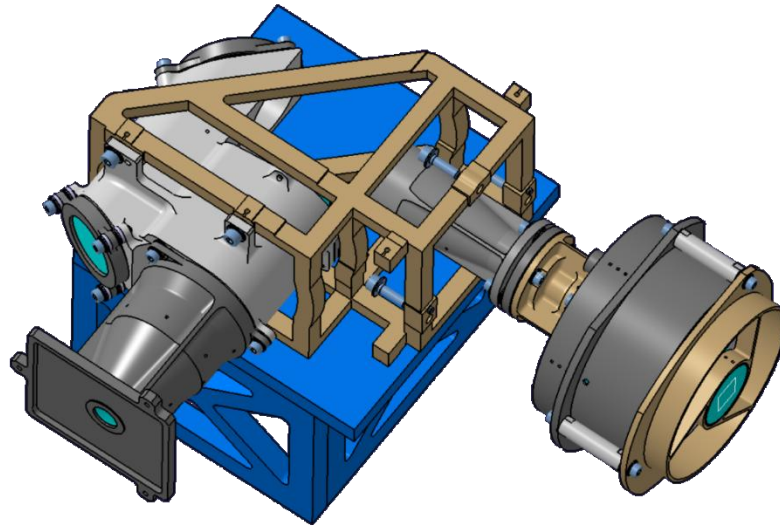


Figure 11. Telescope and spectrometer assembly.

At this point, previous to the insertion of the FPA, a second adjustment of the folding mirror FM2 (compensator) is performed to ensure that there is no vignetting at any element through the whole instrument. For that purpose, the telescope primary mirror is illuminated with a collimated beam and a diffusing screen is placed at the output of the spectrometer collector to verify the image size and vignetting. Afterwards, the screen is replaced by a spectrum analyzer to verify the dispersed spectral range.

4.6. FPA assembly and alignment

The FPA assembly is composed by the detector, based on CCD technology for the UV, VIS and nIR spectrometers and CMOS InGaAs detector for SWIR spectrometer and the associated electronics. This subsystem is the last element to be inserted in the instrument (Figure 12).

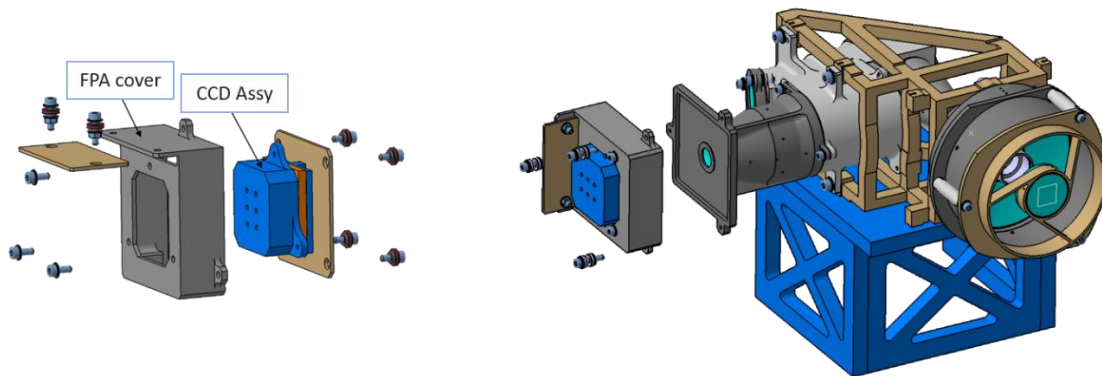


Figure 12. Focal Plane Assembly (left) and FPA assembled to the instrument (right).

The final alignment of the instrument is allowed by the compensators: the tip&tilt of the FM2 and X, Y, Z displacement of the detector. The tip&tilt adjustment of the FM2 is performed by means of the shims mentioned in section 4.4. The displacements of the FPA are performed using a specific tool (Focal Plane Alignment Tool) that is implemented for this purpose and allows the required adjustments (Figure 13). Once the alignment is achieved, the FPA position is fixed by means of three M3 screws and the Focal Plane Alignment Tool is dismantled.

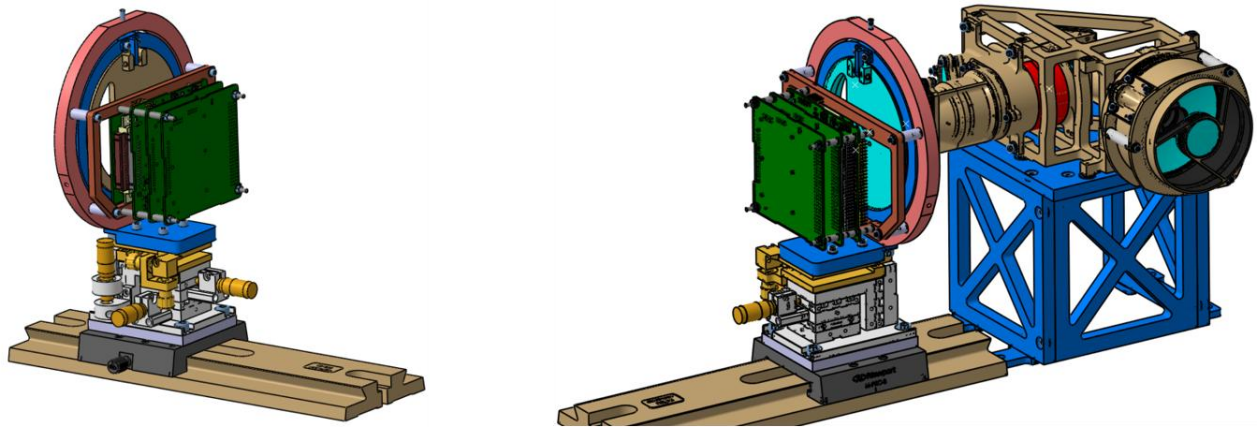


Figure 13. Focal Plane Alignment Tool (left) attached to the FPA for its alignment on the instrument (right).

The success criteria are verified by the analysis of the image: no vignetting and the adequate image size and position on the detector (the pixels in which the image falls and the number of pixels that the image occupies).

4.7. Performance verification

Once the instrument assembly and alignment phases are finished, the performance verification will be conducted. Two different performance tests have been defined, which differ in the type and number of measurements and requirements to be evaluated. The complete performance tests consist of measuring the spectral and spatial resolution, digital SNR, straylight, spectral range, radiometric analysis validation and depolarization degree. While the reduced functional tests consist of the measurement of the position and size of the slit image on the detector which are directly affected if any misalignment occurs during environmental campaigns.

Following it is detailed how the instrument's optical performance will be verified:

- Spectral and spatial resolution: Spatial resolution is obtained from the size of the slit image on the detector (the number of pixels it occupies) and spectral resolution is obtained from the measurement of linear dispersion between two wavelengths separated certain nanometers for each spectral range.
- Digital SNR: It is calculated from the relation between the signal arriving at the detector from a light source and the measured detector noise.
- Straylight: The out-of-field straylight is measured from the energy on the detector when illuminating at different positions out of the field of view of the instrument.
- Spectral range: It is verified by the measurement of the spectral transmission of the interferential filters through a spectrophotometer.
- Radiometric analysis validation: The objective of the test is to verify that the instrument can distinguish between the minimum differences of radiance. In addition, it shall be ensured that the instrument can measure the maximum and minimum radiances at the specified integration time, for each spectral range and radiance level, without saturating the detector. For this purpose, an integrating sphere is utilized to simulate different radiometric scenarios.
- Depolarization degree: It is verified by the measurement of the depolarization degree performed at unit level (scrambler unit).

4.8. FPA defocus for vacuum conditions

Once the integration and alignment of the instrument is completed in ambient conditions, the spectrometer must be adjusted to the operation environmental conditions, it means that the position of the FPA must be defocused to recover the performances when the instrument is operating at vacuum conditions. Table 2 shows the displacement required for the FPA of each instrument (negative sign means that the FPA is moved towards the collector).

Table 2. Vacuum defocus required for each spectral range.

Spectral range	Vacuum defocus (μm)
UV	-74
VIS	-69
nIR	-82
SWIR	-49

5. OPTICAL AND MECHANICAL GROUND SUPPORT EQUIPMENT AND TEST FACILITIES

The next Table 3 shows Ground Support Equipment (GSE) needed for the correct assembly and test of the ANSER-AT payload during AIV (Alignment, Integration and Verification) phase. The GSE is divided in the Optical Ground Support Equipment (OGSE) composed by typical optical instrumentation and the Mechanical Ground Support Equipment (MGSE) composed by jigs and supports that will be required during integration and verification activities. The table summarizes the OGSE and MGSE required for each step of the alignment an integration process, as well as the integration step where it will be used. Additionally, other GSE as Electrical Ground Support Equipment (EGSE) for image acquisition is crucial to be optimized for the AIV process.

Table 3. OGSE and MGSE description.

Step description	OGSE/MGSE
Collimator and collector optical quality verification	MTF Optical Bench, Support tool
Telescope integration and optical quality alignment	FARO Arm, Hexapod, Interferometer, Theodolite, Support tool, Alignment jigs
Collimator integration with telescope and collimation degree verification	FARO Arm, Hexapod, Illumination source, Filters, Shear plate, Support tool, Alignment jigs
Spectrometer assembly in the main body	FARO Arm, Hexapod, Polarimeter, Power meter, Support tool
Spectrometer main body integration is structural bracket	FARO Arm, Hexapod, Support tool
FPA integration and alignment	Illumination source, Filters, Support tool, Alignment jigs
Optical performance verification	Monochromator, Illumination source, Integrating sphere, Filters, Fibers, Power meter, Support tool

The AIV process will be completed at the National Institute of Aerospace Technology (INTA) in an ISO-7 cleanroom that belongs to the Space Optics Department. It is an existing clean area ($\sim 70\text{m}^2$) with cleanliness level ISO-7 equipped with relative humidity, temperature and contamination control systems following the ESA ECSS-Q-ST-70-01C standards for optical instrumentation. This laboratory is specifically equipped with instrumentation to carry out integration and test of optical systems.

6. CONCLUSIONS

A plan for the alignment, integration, and verification of the ANSER-AT mission payload has been established. The payload consists of a segmented spectrometer, with each instrument operating over a different wavelength range. A realistic integration plan has been defined to ensure that the instrument can be assembled while meeting the optical performance

requirements driven by the mission's scientific objectives. In addition, all the required Optical Ground Support Equipment (OGSE) and Mechanical Ground Support Equipment (MGSE) necessary to successfully carry out the alignment process have been identified.

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