International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

Sentinel-5/UVNS

J. Irizar

M. Melf

P. Bartsch

J. Koehler

et al.

icso proceedings

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 1118004 · © 2018 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2535923

Sentinel-5/UVNS

J. Irizar*[a], M.Melf[a], P. Bartsch[a], J. Koehler[a], S. Weiss[a], R. Greinacher[a],
M. Erdmann[b], V. Kirschner[b], A. Perez Albinana[b], D. Martin[b]
[a]Airbus Defence and Space GmbH, Germany; [b]European Space Agency, Netherlands
*juan.irizar@airbus.com; phone +49 89 3179 9077; fax +49 89 6072 6039; www.airbus.com

ABSTRACT

Sentinel-5/UVNS instrument is an Earth atmospheric monitoring spectrometer developed within the Copernicus program. The mission objective is to monitor the chemical composition of the Earth's atmosphere on a daily basis. Airbus Defense and Space GmbH acts as the prime contractor for the instrument under a European Space Agency contract.

The current paper will focus on four themes. First it will provide a brief historical and technical overview of the Sentinel-5/UVNS instrument. Second, the key design drivers will be described. Third, the key optical technologies carried on board the instrument will be elaborated. Finally, the paper concludes with a short look at the current state of the instrument's development cycle.

Keywords: Earth observation spectrometer, Sentinel-5/UVNS, Copernicus

1. INTRODUCTION

The need for routine observations of atmospheric chemical composition from space developed in the mid 1980 with the discovery of large springtime stratospheric ozone depletion (ozone holes) over Antarctica (1). The European Space Agency (ESA) responded to this need with the launch of GOME in 1995. GOME's great success was the measurement of the total ozone column on a planetary scale.

Following this achievement, and for the next two decades, other great European Earth observation instruments were developed and launched. Sciamachy launched on 2002 on board ESA's ENVISAT, GOME-2, flying on Metop First Generation with launches on 2006, 2012 and 2018, OMI flying onboard NASA's Aura and launched in 2004, and TROPOMI launched in 2017 as a part of the Sentinel-5/UVNS Precursor mission.

Continuity of the European Earth atmosphere monitoring heritage falls now to the Copernicus Earth Observation Programme headed by the European Commission. The scope of the programme encompasses a large variety of targets including Earth monitoring (land, oceans, and atmosphere), climate change science, emergency management, and security applications. Observations are supported by satellites, ground based station, and air borne sensors. The space component is supported by the European Space Agency with the development of the Sentinel missions of which Sentinel-5/UVNS is part of.

Sentinel-5/UVNS will be carried on board the MetOp Second Generation Satellite A. Its mission objective is to provide atmospheric daily global coverage of the planet from its sun-synchronous orbit targeting a variety of data products including: ozone, nitrogen dioxide, sulphur dioxide, methane, formaldehyde, carbon monoxide, and some aerosols.

2. SENTINEL 5 OVERVIEW

The Sentinel-5/UVNS instrument is a push-broom passive spectrometer. It covers the spectral range of 270nm to 2385nm with a spectral resolution between 0.25nm and 1nm and a spatial resolution down to 7.5km by 7.5km. The field of view is of 108.4 degrees. The main instrument parameters are summarized in Figure 1.

Customer	European Space Agency (ESA)
Mission objectives	Continuous measurement of the chemical composition of the atmosphere, monitoring of air quality, climate change impact, concentration of aerosols as part of the Copernicus program
Mission orbit	MetOp-SG-A, sun-synchronous ca. 825 km altitude
Spectral range	• Ultraviolet 1 270 to 300 nm • Ultraviolet 2 - Visible 300 to 500 nm • Near Infrared 685 to 710, 745 to 773 nm • Short Wave Infrared 1 1590 to 1675 nm • Short Wave Infrared 3 2305 to 2385 nm
Spectral resolution	1 nm to 0.25 nm depending on the spectral range
Swath width	2,670 km
Spatial resolution	7.5 km x 7.5 km
Data volume	80 Gbit per orbit
Electrical power	<290 W
Service life	>7 years
Optical module components	• Telescope & Beam Splitter Assembly • UV1 Spectrometer Optics • UV2VIS Spectrometer Optics • NIR Spectrometer Optics • UVN Focal Plane Assemblies • SWIR Spectrometer Subsystem • Calibration Subsystems • Structure and Radiators • Thermal Hardware • Front End Electronic • Detection Support Electronics • Instrument Control Subsystem • Harness
Weight	292 kg
Size	1.0 x 1.6 x 1.2 m
Launch	PFM 2021; FM2 2028; FM3 2035
Prime contractor	Airbus Defence and Space GmbH

Figure 1 – Sentinel 5 characteristics

The optical layout of the instrument consists of two separate telescopes assemblies, five spectrographs, and two calibration units. Figure 2 provides a visual representation of the system's modularity.

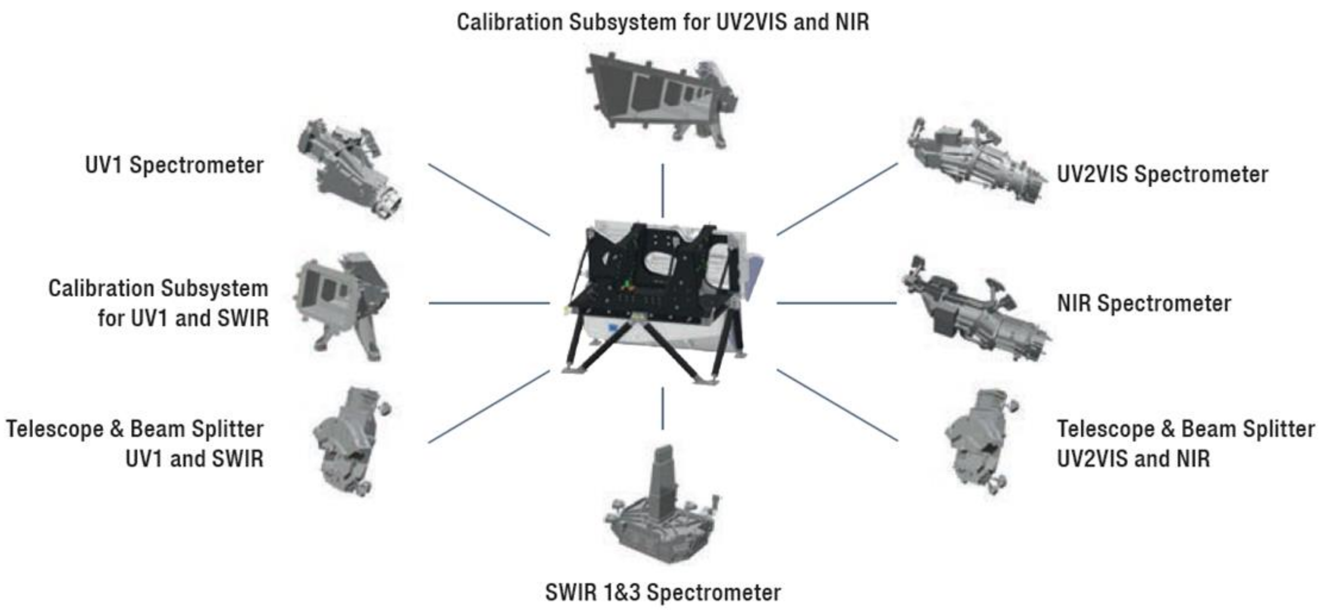


Figure 2 – Sentinel 5 layout

The first telescope assembly, *Telescope and Beam Splitter UV1 and SWIR*, consists of a reflective telescope, a polarization scrambler, a beam splitter, and the so called UV1-slit homogenizer. Light from the earth traverses this unit and at the beam the ultraviolet range is directed towards the UV1-slit homogenizer and consequently into the *UV1 Spectrometer*. The SWIR ranges passes through the *SWIR1 spectrometer and SWIR3 spectrometer* subsystem which contains a dedicated slit homogenizer for the SWIR spectral range. A *Calibration Subsystem* is coupled to the entrance pupil of the telescope.

The second telescope assembly, *Telescope and Beam Splitter UV2VIS and NIR*, is also a reflective telescope, and it also includes a polarization scrambler, a slit homogenizer, and a beam splitter. Light from the earth travels through the telescope, passes a common slit homogenizer, and is then split by the beam splitter to feed the *UV2VIS spectrometer* and the *NIR spectrometer*. A *Calibration Subsystem* is also linked to this telescope.

A Sentinel-5/UVNS mock-up was commissioned by ADS in the instrument post-PDR context and it is shown in Figure 3.

Figure 3 – Sentinel 5 mock up

3. DRIVING REQUIREMENTS

The scope of the technical work as captured by the Sentinel-5/UVNS System Requirement Specification is wide. It includes challenging observational requirements which drive not only instrument design aspects, but also data processing and calibration activities. In this work, the focus is mainly on instrument design aspects and their associated optical technologies.

As shown in Table 1, the observational requirements may be divided into three broad categories: spectral, spatial, and radiometric. Some of the most challenging requirements within each category are provided in the second column of the table. In addition, the third column showcases some of the state of the art technologies that are employed to address the observational need of the mission. The next chapter focuses on providing additional insight into the innovation and challenges associated with these technologies.

Table 1 – Summary of driving observational requirements

Requirement Category	Requirement name	Requirement	Optical technology
Spectral	ISRF knowledge	ISRF shape shall be known to an accuracy of <2% ISRF FWHM shall be known to an accuracy of <1%	**1.** Slit homogenizer
	Spectral resolution	The spectral resolution shall be: 1nm for the UV1, 0.5nm for the UV2VIS spectral range; 0.4nm for the NIR; and 0.25nm for the SWIR spectral ranges.	**2.** Dispersive elements
Spatial	Spatial FoV and spatial resolution	The FoV in act direction shall be at least 108.4deg. The Integrated Energy of the system for an area corresponding to 1SSD x 1SSD shall be: 0.7<IE for UV1; 0.73 ≤ SIE ≤ 0.83 for UV2VIS and NIR; 0.66 ≤ SIE ≤ 0.76 for SWIR	**3.** Free form optics
Radiometric	Absolute spectral radiometric accuracy	The Absolute Radiometric Accuracy of the system shall be: <3% for UV1 to NIR bands; <6% for SWIR1; and <3.5% for SWIR3	**4.** Straylight coatings **5.** Polarization scrambler **6.** Diffuser

4. KEY OPTICAL TECHNOLOGIES

4.1 Slit homogenizers

A slit homogenizer is a technology employed on a space mission for the first time on board Sentinel-5/UVNS. The need for this technology arises from the high likelihood that inhomogeneous Earth scenes, due to cloud formations or the sharp start of a body of water for example, will fall within the instantaneous field of view of the instrument. The telescope images the inhomogeneity onto its focal plane, corresponding to the slit location in a traditional spectrograph configuration. For the sake of simplicity assume that the scene is monochromatic. If the inhomogeneity occurs across the slit (in the spectral direction) the barycenter of the spectrum will wander spectrally introducing an unknown error in the measurement.

To overcome this limitation, Sentinel-5/UVNS uses a slit homogenizer. It consists of two glass blocks as shown in Figure **4**. One face of each block is coated with a highly reflective coating while the other faces are coated with a light absorbing coating. The reflective face of each block is brought into close proximity so as to create a crevice or slit by the use of spacers.

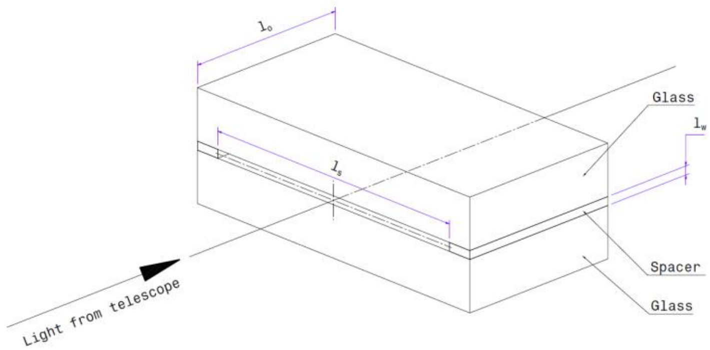


Figure 4 – Slit homogenizer. Configuration of the slit homogenizer highlighting relevant parts

The slit homogenizers in Sentinel-5/UVNS have a slit width (lw) in the range of hundreds of microns, and a slit length (ls) and optical length (lo) in the range of tens of mm.

The *Entrance Plane* is then placed at the telescope focal plane. Light from the telescope can propagate through the homogenizer by bouncing off the reflective surfaces until it reaches the *Exit plane*. Superposition of the virtual images corresponding to each reflection will result in an intensity distribution at the *Exit plane* which is more homogenous that the distribution at the *Entrance plane*. The slit homogenizer then solves the potential spectral wandering introduced induced by inhomogeneous scenes at the expense of introducing anamorphism into the spectrograph optics. Indeed, the spectrograph's collimators retrieve the spatial content from the *Entrance Plane* of the homogenizer and the spectral content from the *Exit Plane* of the homogenizer.

In order to understand the benefit of this rather technically challenging solution, consider the simulated response of the Sentinel-5/UVNS instrument to real ground scenes in the UV2VIS spectral range as seen in Figure **5**. The left panel is related to the case in which the Sentinel-5/UVNS slit homogenizer is reduced to a traditional slit (ie the optical length becomes 0.00mm). Four irradiance curves are shown on the plane of the slit on the across-slit direction: A heterogeneous scene on the ground, the same scene after the smearing due to the motion of the platform, the scene obtained at the exit plane of the homogenizer (in this case the same as the second scene), and finally a uniform scene. Note that the barycenter difference between the third and fourth curves will induce spectral wandering.

On the right panel of Figure **5**, the same four curves are shown. Except that this time, the slit homogenizer, with its nominal UV2VIS dimensions, is present. The outcome is the irradiance distribution of the third and fourth curve features no significant deviation of the barycenter thus avoiding the spectral wandering error.

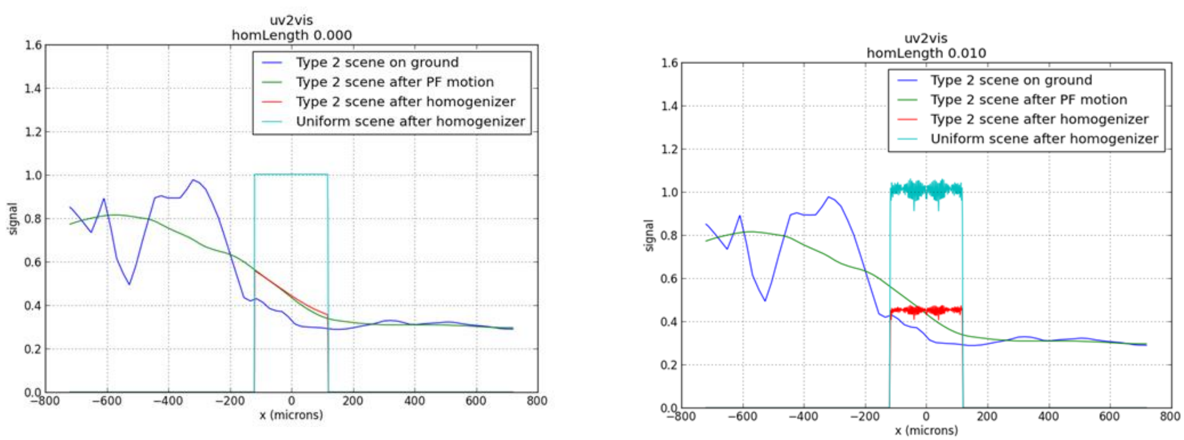


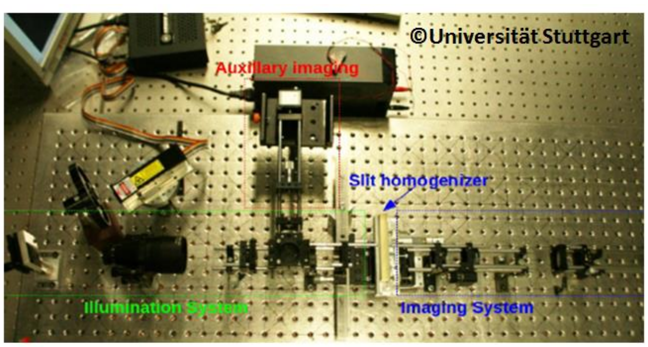
Figure 5 – Sentinel-5/UVNS response to different scenes. Left: No slit homogenizer. Right: With a Slit homogenizer. In each case note the differences between the light blue and the red curves.

The slit homogenizer technology has been successfully proven through several dedicated breadboards by TNO Delft. First, the slit homogenizer sub-assembly is a complex opto-mechanical device. At the start of the project, questions regarding the manufacturability, integrability and alignment, and stability under the expected thermo-mechanical environments, were critical. The outcome of a dedicated breadboard addressing these concerns was positive in all respects. Figure 6 provides some images of these activities.

Figure 6 – Slit Homogenizer breadboard showing manufacturability, alignment, and stability of assembly. Left: Bonding of homogenizer in its mount. Right: Slit homogenizer assembly on the vibration adaptor plate

A second breadboard was commissioned to ensure that the expected optical performance of the slit homogenizer (ie the smearing of the irradiance at the Entrance Plane) was as achievable with the required quality.

Figure 7 showcases the optical setup constructed for this purpose featuring a monochromatic point source (laser) illumination, which is imaged onto the slit Entrance Plane by illumination optics representative of the Sentinel-5/UVNS telescope. The irradiance distribution at the Exit Plane is then image onto a detector by the Imaging System. The measurements can then be validated against simulated predictions of the irradiance patterns. The outcome of the breadboard gave confidence that the slit homogenizer design was providing the required optical performance.



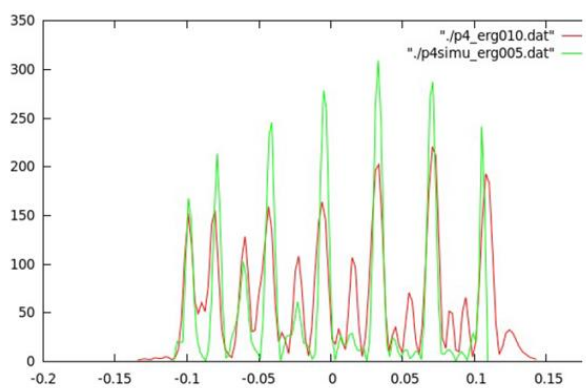


Figure 7 – Slit homogenizer breadboard targeting validation of optical performances by ITO Technical University Stuttgart. Left: Optical setup including illumination system, imaging system, and slit homogenizer. Right: Irradiance pattern at the *Exit Plane* of slit homogenizer. Illumination consists of a monochromatic point source. Green: Simulated. Red: Measured

4.2 Dispersive elements

An integral part of any spectrometer is the dispersive element. Sentinel-5/UVNS makes uses of extensive state of the art technology to accommodate for the design and performances needs of each of its five spectrographs. Table 2 provides an overview of the type of dispersive elements found in Sentinel-5/UVNS together with some of their unique characteristics

Table 2 – Dispersive elements overview

Spectrograph	Dispersive element type	Diffraction mode	Characteristics
UV1	Grating	Reflection	- Grating etched on a convex conical component - Grating used off axis
UV2VIS	GRISM	Transmission	- Grating is etched directly on a monolithic prism
NIR	Grating	Transmission	- Holographic recording - Followed by atomic layer deposition to fine-tune grating
SWIR1	GRISM	Reflection	- Immersed Grating - Silicon substrate
SWIR3	GRISM	Reflection	- Immersed Grating - Silicon substrate

The dispersive element is critical since it contributes directly to several instrument performance metrics including straylight, throughput, polarization sensitivity, and spectral properties.

The emphasis of this work is on the UV1 grating. The latter is a reflective grating etched on a substrate of fused silica with an aluminum top layer. The underlying morphology of the substrate corresponds to a convex surface with a radius of curvature and a conical constant. The grating is used off axis and its line spacing is constant in projection.

The development of the Engineering Model (EM) gratings has been completed by Carl Zeiss Jena and TNO Delpht demonstrating the feasibility to manufacture the UV1 grating on an aspherical substrate and in compliance to the UV1 needs. In particular, as shown in Figure 8, the aspherical shape of the substrate can be manufactured to the required accuracy.

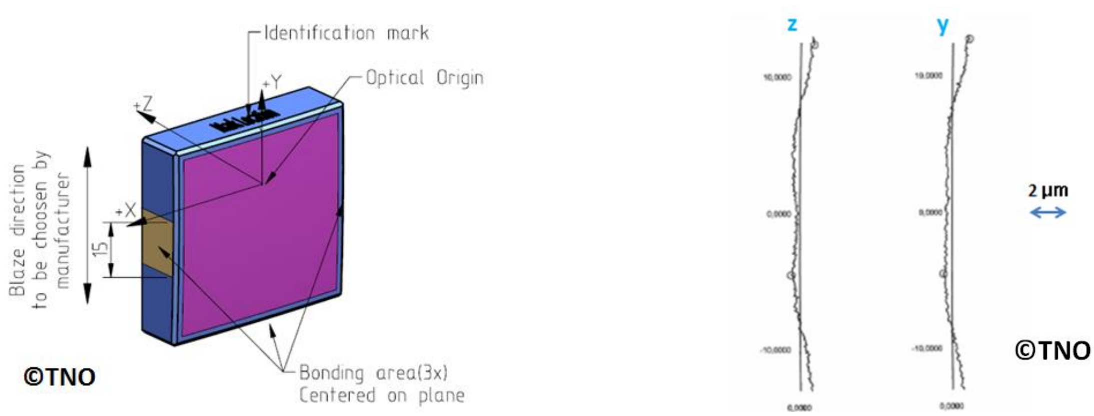


Figure 8 – UV1 grating. Left: Grating specification showing optical origin and other details. Right: Tactile measurement of the EM gratings along the Y and X axis. The ideal aspheric shape was corrected and the deviation is plotted, scan length 26mm around the vertex

In addition, the recording of the grating pattern on the aspherical substrate yields excellent performances in diffraction efficiency as demonstrated on the left panel of Figure 9. In what concerns polarization sensitivity, the manufactured gratings showed compliance to the requirement specification for most of the spectral range as shown on the right panel of Figure 9. Nevertheless, small non-compliances were obtained for the wavelengths neighboring the 280nm.

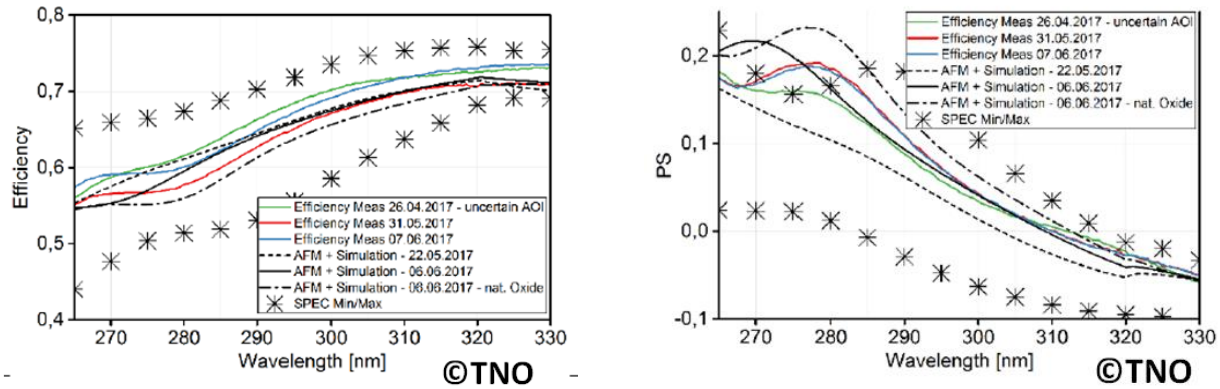


Figure 9 – UV1 grating performances. Left: Diffraction Efficiency. Right: Polarization Sensitivity

In terms of straylight, the manufactured gratings yielded the BRDFs reported in Figure 10. The manufacturing of the substrate yields a surface with very low scattering relative to the requirement. Nevertheless, the etching of the grating lines naturally increase the level of straylight from the grating to levels that are slightly above the BRDF specified for this component.

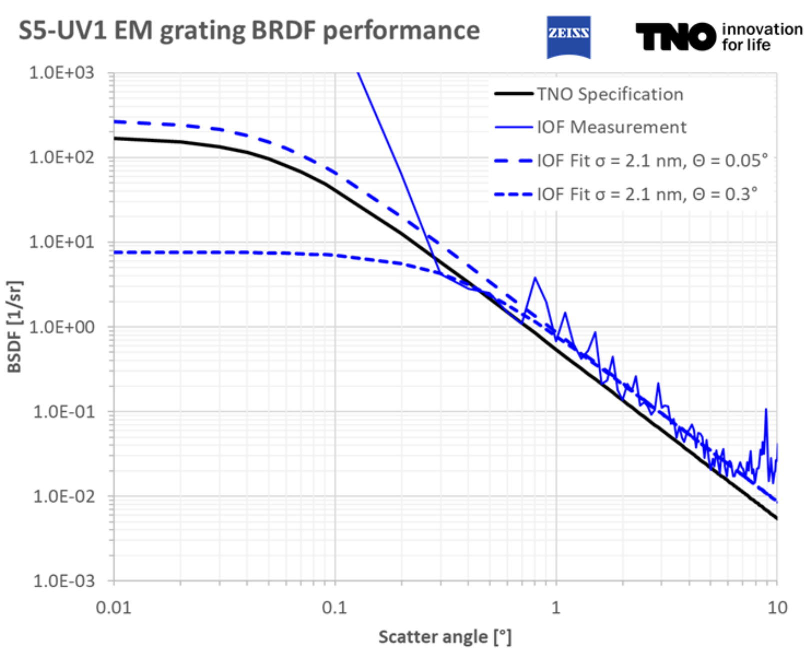


Figure 10 – UV1 EM grating BRDF performances

4.3 Free form optics

The innovation of Sentinel-5/UVNS is that it will provide atmospheric spectra within a field of view of more than 108deg with unprecedented spatial resolution, high co-registration between spectral bands, and high radiometric accuracy. In order to achieve these features, within the weight and dimensional constraints available for the instrument, free form components have been used. A traditional three mirror anastigmatic telescope for example would have enough degrees of freedom to satisfy the needs of the Sentinel-5/UVNS telescopes. Nevertheless, by the introduction of free form optics, two instead of three optical surfaces can be used resulting in weight and space savings. The optical design of the Sentinel-5/UVNS telescopes is shown in Figure 11.

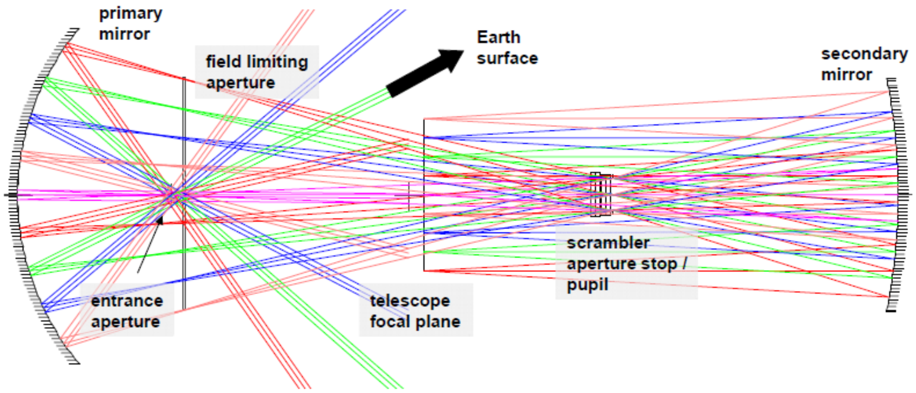


Figure 11 – Design of the Sentinel-5/UVNS telescopes

The telescopes feature a two-mirror reflective design which is telecentric on the image side. The large FoV in across track direction, the image telecentricity, the presence of an accessible intermediate field plane where the field stop is paced, and accessible intermediate aperture plane with reduced angle spectrum where the aperture stop and polarization scrambler assembly are located, and the demanding throughput requirements are the drivers for the use of freeform reflective optics.

The demands on the telescope mirrors are clear: low roughness for straylight control, adequate slope error to guarantee co-registration, adequate surface shape error to guarantee image quality, and opto-mechanical decoupling from specially detrimental AIT loads. In order to increase the technology readiness level of such difficult components, the Sentinel-5/UVNS project started dedicated manufacturing breadboards for the first mirror prepared by TNO Delpht.

Figure 12 – Mirror 1 manufactured for the breadboard program

The manufacturing process to produce such mirrors is challenging. It includes milling step of the aluminum substrate, a first diamond turning targeting the development of the freeform into the surface, a second diamond turning targeting mid-spatial deformations, and a post polishing to achieve an adequate surface micro-roughness.

The breadboard outcome was successful in all respects as shown in the table below:

Table 3 – Outcome of mirror 1 breadboard

Item	Requirement	Breadboard outcome
Surface roughness	<0.7 nm	0.54 nm
Slope error	<50 microrad	50 microrad
Surface form fit (power deviation)	2.18 μm	336.6 nm
Surface irregularity (sphere)	1.09 μm	388 nm

4.4 Stray light suppressive coatings

The L0 Sentinel-5/UVNS straylight requirement is exceedingly challenging. It requires that the level of straylight be less than 1% of the nominal light. The requirement is applicable when the instrument looks at complex scenes which contain spectral as well as spatial content. The straylight requirement drives to a large extent manufacturing processes of the optics, cleanliness levels, as well as the need for straylight suppressing coatings.

Without a doubt, one of the most challenging coatings in the Sentinel-5/UVNS instrument is the so called Linear Variable Filter Coating (LVFC) located on the surface looking towards the detector on the last camera element (CAM6) in the UV2VIS spectrograph. This is shown on Figure 13.

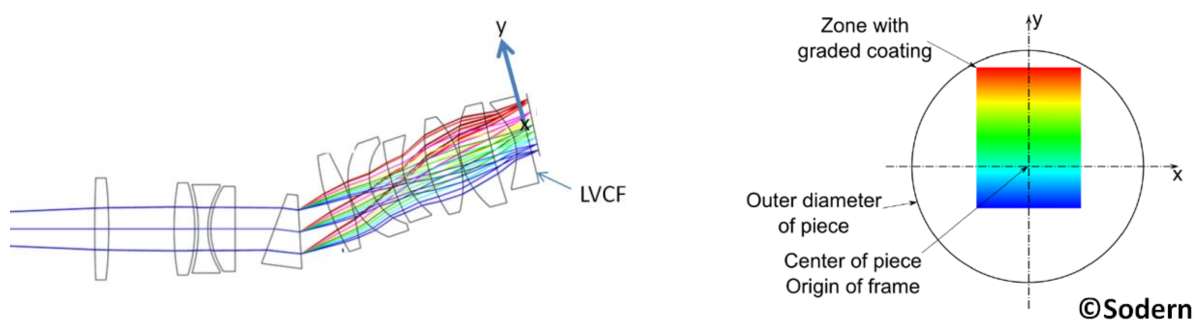


Figure 13 – The LVFC coating is one of the most complex straylight suppressing coatings on board. Left: Position of the LVFC on the UV2VIS spectrograph. Right: Detail of CAM6 lens showing positioning of LVFC

The LVFC is essentially a spectral low-pass filter whose cutoff wavelength changes spectrally along the detector. Figure 14 illustrates the point by providing the computed transmittance of an early breadboard commissioned by Airbus Defence and Space GmbH. In particular, when the coating is homogeneously and monochromatically illuminated with a particular wavelength λ_o, the region of the coating that would be looking down at detector pixels with wavelength assignment of λ_o, or less, allow light to pass through. Regions in the coating that would look down upon detector pixels with assigned wavelengths larger than λ_o, attenuate the light. This behavior ultimately implies that a given detector pixel with wavelength assignment λ_o, is shielded from radiation larger than λ_o. This is extremely useful since the natural earth spectrum in the UV2VIS regime features light starvation in the low wavelength ranges.

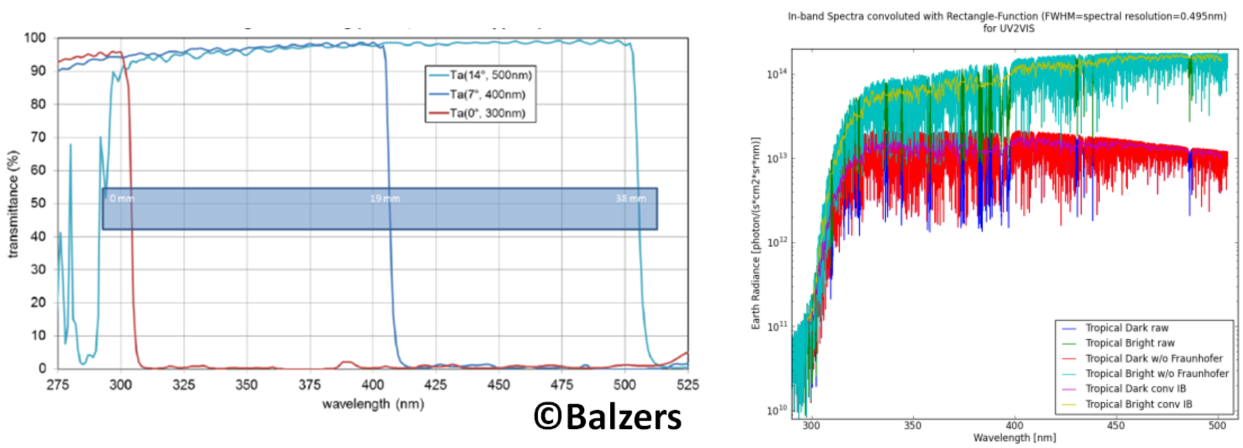


Figure 14 – LVFC use. Left: Simulated transmittance of a preliminary LVFC design. Right: Earth radiance in the UV2VIS regime. Straylight from the light rich regime (upper wavelengths) heavily pollutes detector pixels with low wavelengths

Achieving the required performances from the LVFC is not an easy task. Specially challenging is the obtaining the necessary sharp cut-offs across the spectral domain, a high throughput in the high-pass region, and the suppression of resonances across the transmission profile. Several breadboards have been commissioned throughout the development cycle of the UV2VIS spectrograph targeting improvements in the aforementioned areas. Figure 15 shows the result of one of the latest breadboards.

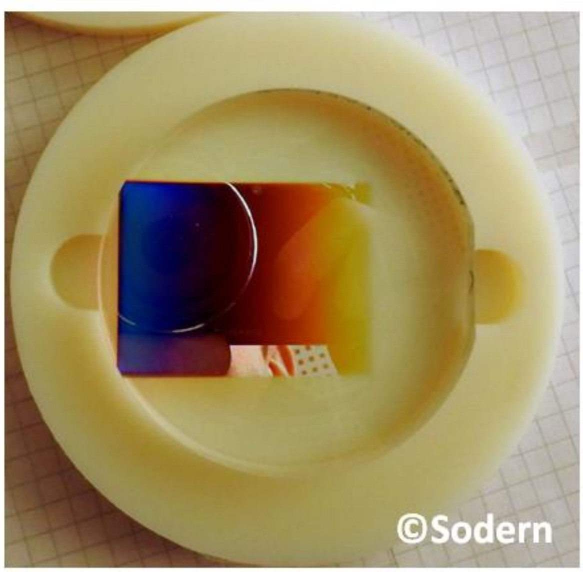


Figure 15 – LVFC breadboard Image of one of several LVFC coating developed within the breadboard program

Ultimately, the manufacturing and design challenges associated with the LVFC are compensated by the extremely beneficial impact the coating has on the L0 instrument performance. Figure 16 shows the straylight ratio of an instrument tin which the LVFC coating is absent to that in which the LVFC coating is present. Overall, the LVFC reduces the overall straylight level by a factor of seven.

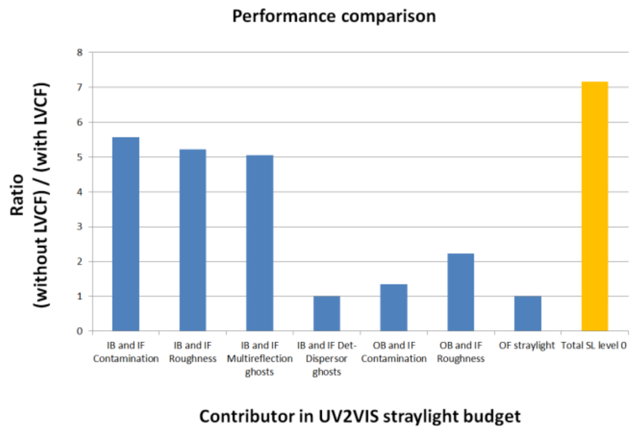


Figure 16 – Improvement of straylight budget due to LVFC

4.5 Polarization Scrambler

The L0 polarization requirements stipulate that the polarization sensitivity shall be less than: 0.5% for the UV2VIS and near NIR range, 0.7% for the far NIR range, and 20% for the SWIR range. In this context, polarization sensitivity is defined as the ratio $P = (S_{max} - S_{min})/(S_{max} + S_{min})$ where S_{max} and S_{min} are the maximum and minimum sample values obtained when the scene (linear) polarization is rotated gradually over 180 degrees.

Scenes from the Earth can be heavily polarized. In addition, several components within the instrument have a response function that is highly sensitive to the polarization of the incoming light. These include,primarily the different types of gratings, the HR coatings of mirrors, the AR coatings of the refractive elements, and also special coatings like the LVFC. If left unattended, the combination of a highly polarized input radiation with a highly polarization sensitive instrument would result in measurements that introduced a large amount of absolute and relative radiometric errors causing non-compliance to the instrument radiometric accuracy and polarization requirement. For this reason, scrambling the polarization of the incident light by a scrambler is necessary.

The polarization scramblers (one per telescope) in the Sentinel-5/UVNS instrument are a variant of the Dual Babinet Compensator Pseudo depolarizer (DBCP). As illustrated on Figure 17, each scrambler is made up of four wedges (W1 to W4). The wedge shape in the birefringent wedges (W1 and W4) induces a s-p retardation that varies over the beam cross-section. Wedges are paired to counter the deflection of the beam and increase the depolarizing effect. A second wedge pair (W3 and W4) is needed to depolarize light that is polarized parallel or perpendicular to the optic axes of the first wedge pair (W1 and W2). The first two wedges have a rooftop shape to reduce polarization induced pointing variation. The last two wedges are standard prisms. W1 is in optical contact with W2. W3 is optically contacted to W4. Finally, it is important to highlight that the polarization scrambler is placed in a moderately diverging optical beam.

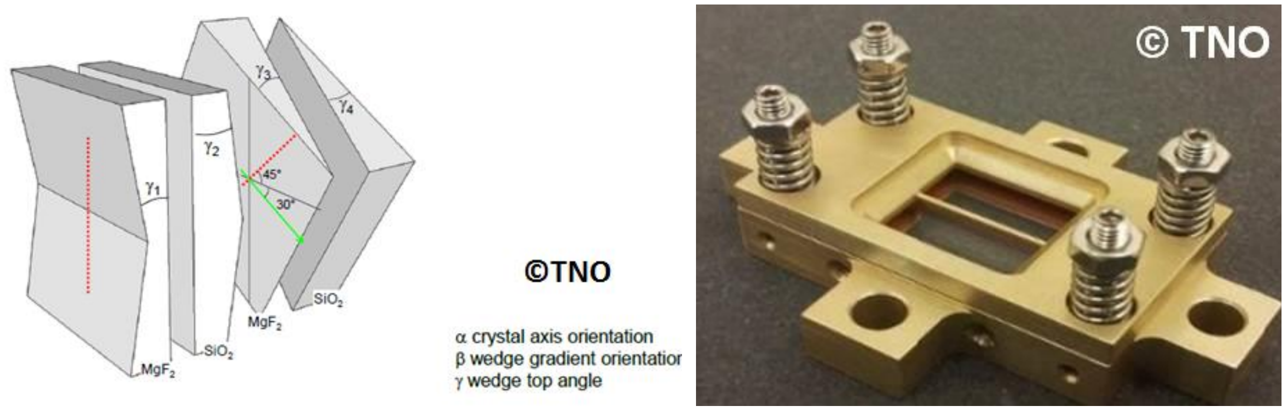


Figure 17 – Sentinel-5/UVNS Scrambler

The design of the scrambler is a complex iterative process. The optimization space is large (scrambler type, optical materials, shape of wedges, orientation of axis, separation of wedges, etc). In addition, as it turns out, the polarization dependence within the *Telescope and Beam Splitter assemblies* is also strongly dependent on the first mirror polarization properties. The outcome of these analytical trade-offs is a scrambler design which was the basis for a bread board program with the aim to prove the manufacturability of the scrambler as well as to ensure that the predicted scrambler's polarization performance was in agreement with the theoretical design.

Figure 18 highlights the breadboard measurement set up prepared by TNO Delpht and on the left, as well as a comparison of the measured and calculated results. Some notable observations are the period and amplitude visible in the measurements is reproduced by the simulations. The phase is not perfectly reproduced but this is attributed mainly to manufacturing imperfections. Nevertheless, the difference between simulations and measurements is of the same order as one would expect on the basis of the tolerance analysis.

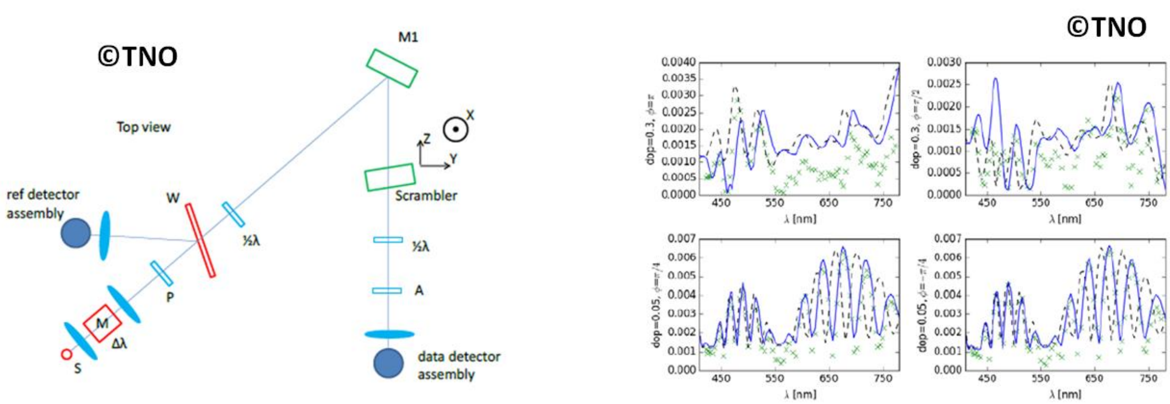


Figure 18 – Scrambler Breadboard. Left: Schematic top view of breadboard measurement set up. Right: Polarization sensitivity vs wavelength. Each quadrant represents the degree of polarization for a different input wavelength. Dashed line: simulation results without manufacturing tolerances. Green crosses: measurement results. Blue line: simulation results of adjusted with manufacturing tolerances

At the instrument level, the decorrelation introduced by the scramblers in the *Telescope and Beam Splitter assemblies* is further degraded by the optical elements that are down the optical train, and especially by the dispersive elements. The polarization sensitivity of all coatings and the dispersive elements is strongly controlled through specifications flowed down to them. Nevertheless, it cannot be brought down to zero. Polarization sensitivities for the entire optical chain have recently been assessed in the context of the upcoming instrument CDR. For simplicity, the NIR path is illustrated in the figure below. It is clear that most fields are compliant with the requirement of 0.5%/0.7%. Even the very extreme field edges are marginally compliant.

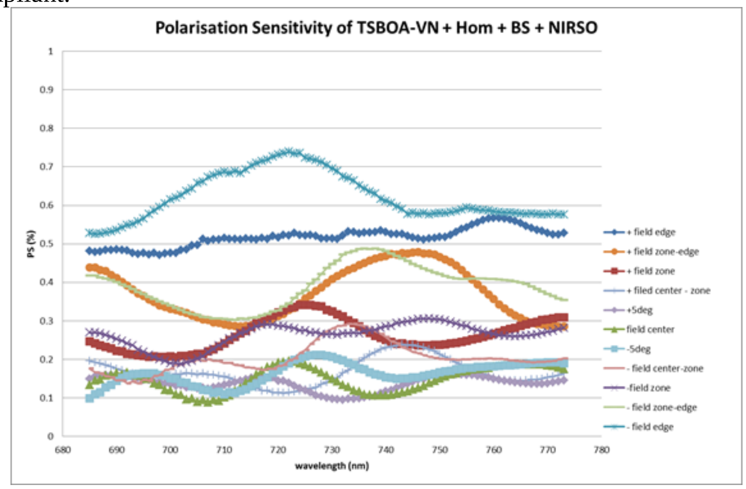


Figure 19 – Polarization sensitivity at instrument level. NIR chain

4.6 Diffuser

Sentinel-5/UVNS incorporates on-board calibration facilities to account for any deviation of the instrument response throughout its operational lifetime: sun calibration, white light sources, spectral light sources, LEDs, aperture closure for dark calibration, and mirror for deep space viewing. These capabilities are implemented in the instrument's Calibration System (CAS) units. There is one calibration subsystem for each telescope providing the required stimuli at the entrance pupil of each telescope. The CAS units feature a rotating wheel able to place the required stimuli at the entrance pupil of the instrument.

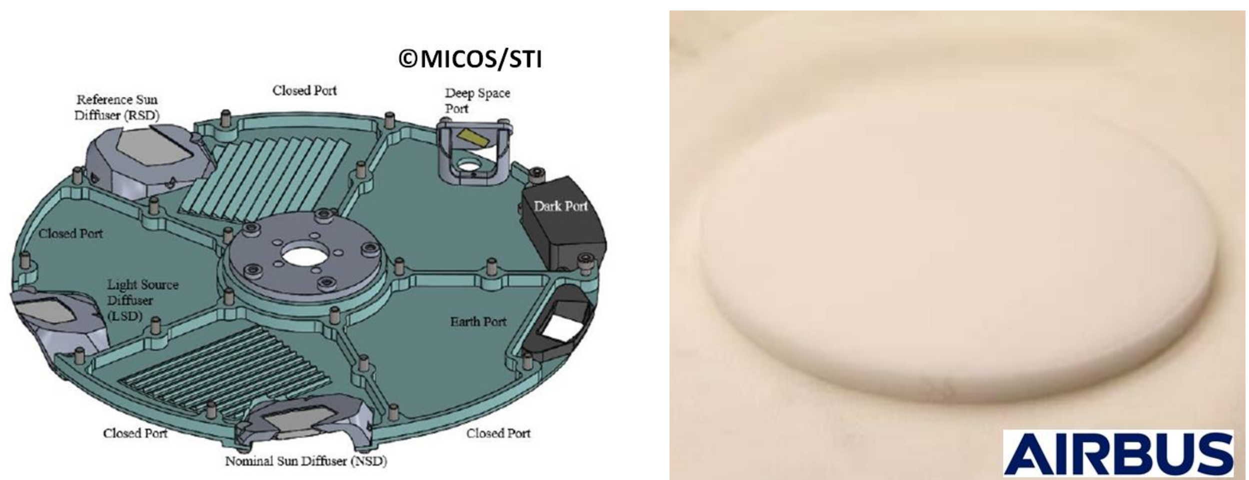


Figure 20 – Left: CAS rotating wheel. Right: HOD-500 diffuser

One of the most interesting components on the CAS rotating wheel is the diffuser. Given the fact that two calibration units are required in Sentinel-5/UVNS, weight was a key design driver for the CAS. An obvious mass saving element was the diffuser itself. The diffuser is a component that ensures homogenous illumination of the homogenizer *Entrance Plane* during sunlight calibration by scattering the incoming light. A variety of diffusers were investigated, mass considerations and optical performonces achieved, being key parameters.

In particular, a synthetic fused silica volume diffuser manufactured by Heraeus (HOD-500) was considered given the compactness of the resulting diffuser as well as the promising improved in optical performances with respect to the more common Quasi-Volume-Diffuser (QVD).

HOD-500 is made of synthetic fused silica, which undergoes a sintering process. The small embedded inhomogeneity's are responsible for the scattering of light. Since a transmission loss in silica glass under UV irradiation is foreseen due to the defects center generation, a collaboration with resulted in a radiation hardened material: *Treated-HOD-500*.

The main issue with *Treated-HOD-500* was the lack of space heritage. This gave rise to the need of performing a full qualification campaign on the material. All tests were completed successfully confirming that *Treated-HOD-500* could be baselined for the Sentinel-5/UVNS instrument.

Table 4 – Airbus Defence and Space GmbH qualification campaign results for treated HOD-500

Qualification test	Outcome for treated HOD-500
Contamination and cleanliness	Best cleaning method is solvents
Humidity	No material degradation
Gamma radiation	No decrease in transmission
VUV radiation	Minimum decrease in transmission
BSDF	Low sensitivity to angle of incidence Small variation with wavelength
Spectral features (speckle)	Spectral features within requirement

For the purposes of this paper, the BSDF performance is of interest. In terms of BSDF, the measurements showed that in general, the *Treated-HOD-500* is a better diffuser (more lambertian profile) than other diffusers used in space applications- The measurement curves for a set of relevant Sentinel-5/UVNS wavelengths are shown in Figure 21.

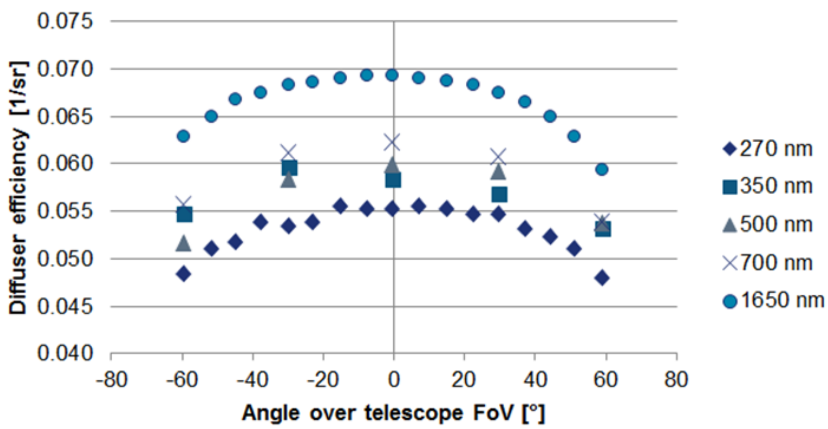


Figure 21 – BSDF measurement for the Treated-HOD-500 diffuser.. Angle of incidence corresponds to angle for which the best diffuser efficiency is obtained

When observing a Sun illuminated diffuser with a spectrally resolving instrument a residual speckle pattern will be observed in the focal plane. The speckle pattern is detrimental in that it reduces the radiometric accuracy of the sun calibration measurement. Thus it is of paramount importance to insure that the speckle pattern produced by the baselined diffuser is compliant to the instrument's calibration needs. Detailed engineering work carried out at Airbus Defence and Space GmbH combined innovative speckle measurements and analysis in order to assess the amount of radiometric error the speckles would introduced (2). The outcome of the exercise was the indirect quantification of the speckle impact on the absolute radiometric accuracy during calibration. Ultimately, the important conclusion is that the *Treated-HOD-500* could serve well the radiometric needs of Sentinel-5/UVNS.

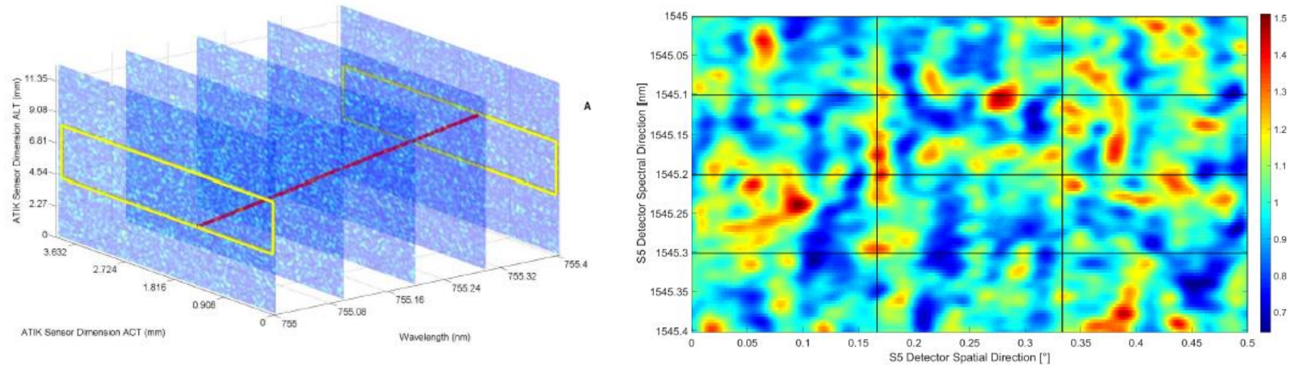


Figure 22 – Speckle measurement and analysis. Left: Data cube of measured data. Input wavelength in the NIR range. Right: Computed speckle pattern on the NIR detector

5. CURRENT STATUS

The development plan of the Sentinel-5/UVNS was elaborated in accordance with specific satellite and verification/qualification needs. It comprises of four different models covering the respective different verification steps for the different domains:

1. Structural Thermal Model. Including instrument structure and S/S mass dummies and used for structure qualification, thermal model correlation, and micro-vibrations assessment
2. Electrical Functional Model (EFM). Used to simulated instrument to platform interfaces, ICS functions, and support procedures development
3. Engineering Model (EM). It includes 2 telescopes, UV2VIS and SWIR-3 channels and 1 CAS. It is used for an optical alignment dry run, as well as performance verification & calibration dry run
4. Proto-Flight and Flight-Models (PFM & FMs). These are the fully verified and calibrated flight models.

The STM is fully assembled and currently undergoing test.

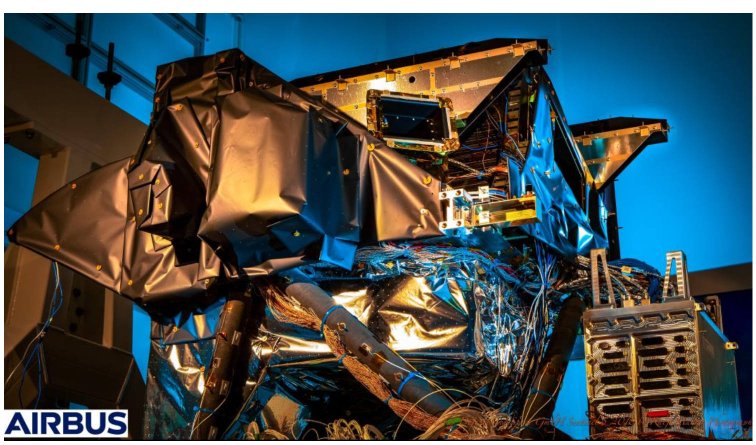


Figure 23 – Sentinel-5/UVNS STM model

Currently, the Sentinel-5/UVNS instrument is preparing for its CDR which is held later in 2018.

6. ACKNOWLEDGEMENTS

The authors would like to thank the whole Sentinel-5/UVNS project team, as well as our industrial partners for their dedication and fruitful cooperation in this challenging project. The authors would like to give special thanks to our industrial partners at TNO in Delft for the collaboration and inputs to this work related to the sections on the slit homogenizer, dispersive elements, free form optics, and polarization scrambler. Thanks to Sodern in Paris also for the cooperation and inputs to the section on the straylight suppressive coatings. And to Micos for the inputs on the diffuser chapter.

.

The Sentinel-5/UVNS project is funded by European Commission under an ESA contract, as part of the Space Component of the Copernicus Programme.

7. WORKS CITED

1. *Sentinel-5/UVNS: the new generation European operational atmospheric chemistry mission in polar orbit.* **Perez Albinana, Abelardo and all.** s.l. : Proc. SPIE 10403, 2017, Vol. Infrared Remote Sensing and Instrumentation XXV.

2. *Sentinel-5/UVNS: a novel measurement approach to quantify diffuser induced spectral features.* **Burns, Tristan and all.** s.l. : ICSO 2016, 2016.