

High-dynamic-range measurements of the wavelength dependence of the specular and diffuse transmissions of optical components in the UV part of the spectrum

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ABSTRACT

The performance of optical instruments used in space can be drastically affected by the use of interferential optical filters whose light transmission or scattering properties do not comply with the specifications derived from those established at the system level. Examples include insufficient out-of-band rejection in the case of a bandpass filter, excessive residual transmission at the design wavelength in the case of a multilayer mirror, or enhanced scattering at wide angles at certain wavelengths in the case of stripe filters used in the focal planes of Earth observation instruments. It is therefore essential to have an optical ground support equipment (OGSE) capable of measuring these optical properties over the widest possible wavelength ranges and with the greatest possible dynamic range. This is achieved by the SALSA (Spectral and Angular Light Scattering Characterization Apparatus) instrument, which has been under development for over 10 years by the Scattering team at the Fresnel Institute in the visible and near-infrared regions (400 nm – 1700 nm), and for which an extension into the ultraviolet (200 nm–400 nm) is currently underway, in order to provide spectral coverage over more than 3 octaves of wavelength. This paper presents the strategy for selecting the various subsystems involved in the operation of such an instrument and provides the initial results of the experimental tests conducted during its integration.

Keywords: OGSE, Optical interference filters, Ultraviolet, Spectral transmittance, ARS

1. INTRODUCTION

Over the past decade, the Scattering Group at the Institut Fresnel has developed an instrument^{1–5} called SALSA (*Spectral and Angular Light Scattering Characterization Apparatus*), with support from CNES. SALSA enables the measurement of the spectral transmittance of an optical component across the entire spectral range from 400 to 1700 nm, with a dynamic range of over 13 orders of magnitude and a spectral resolution of up to 0.15 nm. Thanks to its rotating-arm goniometric configuration, SALSA can also measure the spectral dependence of the scattering parameters (BRDF and BTDF) of the same component. It has an angular resolution better than one-tenth of a degree and a detection floor corresponding to the limit imposed by Rayleigh scattering in ambient air (10^{-8} sr⁻¹).

The working principle of SALSA is based on the following key points (see Fig. 1):

1. the implementation of a powerful broadband light source that is characterized by the highest available spectral radiance in the specified wavelength range,
2. the use of a first stage of spectral filtering that isolates a bandwidth of a few nanometers within the source spectrum with a tunable central wavelength,
3. the crossing of an electro-mechanical shutter that allows the illumination duration to be adjusted between 20 ms and 100 s,
4. the measurement of a small portion (10%) of the filtered light power using a photodiode that is equipped with a low-noise transimpedance amplifier, a programmable gain, and a 16-bit analog-to-digital converter with a 100 kHz sampling rate (reference channel),

5. the crossing of a set of switchable optical densities, that allows the light flux to be attenuated between 0 and 12 OD in steps of one,
6. the launching of the so prepared light flux into a 50- μm core-diameter step-index optical fiber (the emitting fiber) by reflection from an off-axis parabolic mirror,
7. the connection of another step-index optical fiber (the receiving fiber) to the entrance port of a Czerny-Turner spectrophotometer, whose exit port is equipped with a low-noise, thermoelectrically cooled, scientific grade, detector array.

The free ends of the emitting and receiving fibers are each connected to an off-axis parabolic mirror, which respectively illuminates the optical component with a low divergence light beam and collects the light flux transmitted or scattered by it.

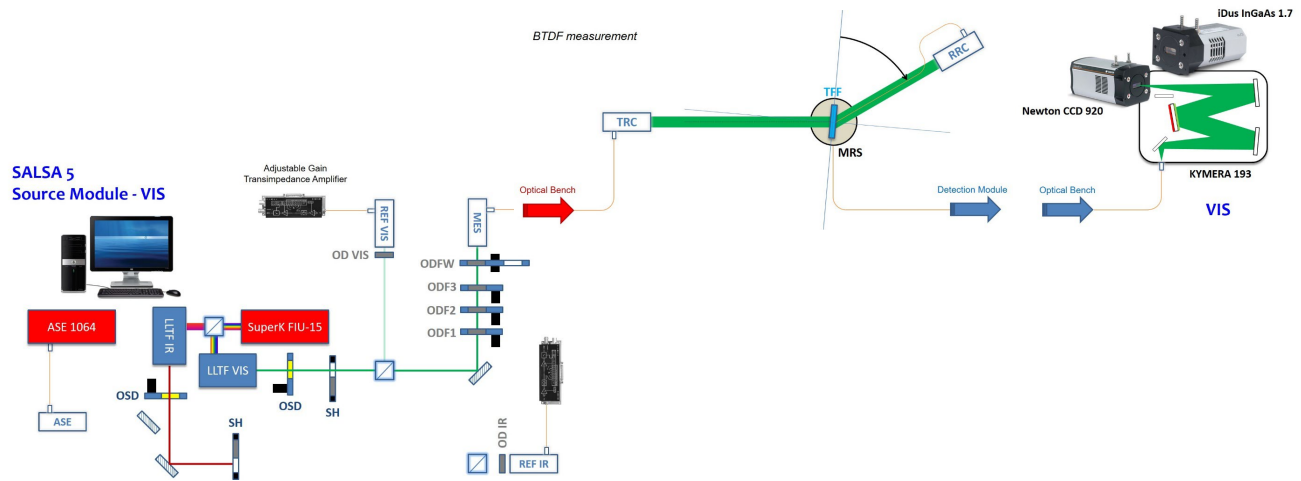


Figure 1. Schematic representation of SALSA

The next section will analyze the consequences of extending the instrument's spectral range to the ultraviolet part of the spectrum (200-400 nm) on all these key points.

2. DEFINITION STUDY

The **light source** used in SALSA is a supercontinuum laser manufactured by NKT Photonics (now Hamamatsu Photonics). Unfortunately, there is currently no supercontinuum laser source that emits significant power below 400 nm. Therefore, another type of broadband source with better spectral radiance performance in the UV must be selected. One option is the laser-driven light source (LDLS⁶), which is manufactured by Energetiq, a Hamamatsu subsidiary. This source utilizes a focused laser beam to generate and maintain plasma between the discharge electrodes in a xenon gas filled bulb (see Fig. 2). An important part of the power is emitted between

Principle of Operation

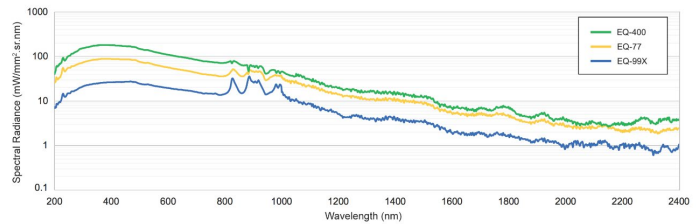
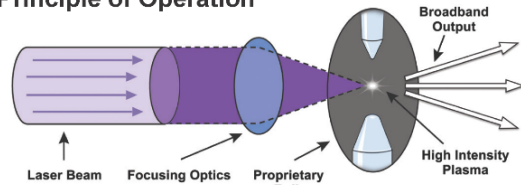


Figure 2. Laser-driven light source⁶ from Energetiq (left: principle of operation; right: spectral radiance)

200 nm and 500 nm, which corresponds to our needs. Three different models are commercially available, EQ-400, EQ-77, and EQ-99X, ordered by their diminishing spectral radiance values. The former two require water cooling, while the latter does not need auxiliary cooling and is available in a fiber-coupled version (EQ-99X-FC-S), offering a good compromise between cost, simplicity, and performance. We selected this fiber-coupled version for SALSA-UV (see the picture at the right side of Fig. 3). In order to support high-brightness UV

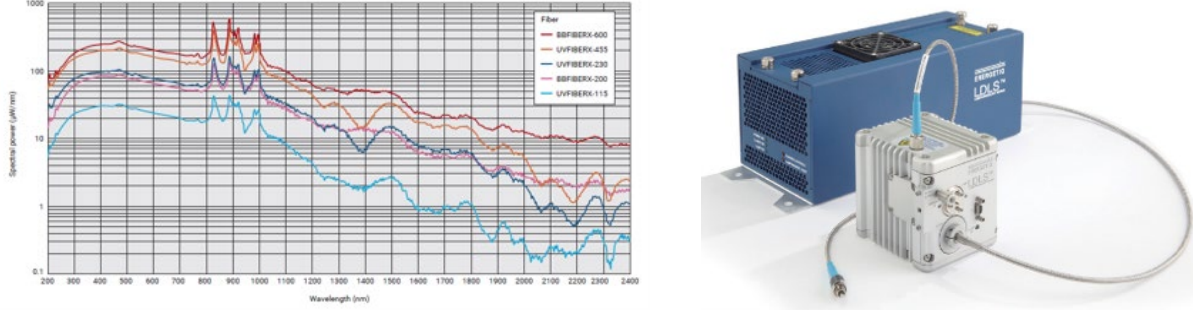


Figure 3. Fiber-coupled laser-driven light source from Energetiq (left: Wavelength dependence of the coupled power spectral density for various fiber core diameters; right: Picture of the EQ-99X-FC-S model)

continuous illumination below 300 nm for an extended period of time without experiencing degradation (i.e., color center creation), this fiber must be solarization-resistant. Additionally, the core diameter should be similar to the plasma size ($100 \mu\text{m} \times 180 \mu\text{m}$) to prevent coupling loss or excessive radiance dilution. With a 115 μm step-index core diameter and a standard 0.22 numerical aperture, the coupled spectral power density is approximately $23 \mu\text{W}/\text{nm}$. This is compared to $75 \mu\text{W}/\text{nm}$ for a 230 μm core diameter (see graph on the left side of Fig. EQ-99X-FC-S). Note that this choice is not final due to the presence of an FC/PC mating sleeve mounted directly on the source housing wall, which allows fibers to be exchanged when required (see the picture on the right side of Fig. 3).

The standard version of SALSA uses a tunable volume hologram filter (LLTF, or Laser Line Tunable Filter) for the **first stage of spectral filtering**. This filter is manufactured by Photon etc and characterized by high transmission efficiency (up to 65%) and an extremely low out-of-band rejection level (less than -60 dB at ± 40 nm). Unfortunately, the lowest central wavelength that can be reached with such a device is 400 nm. Therefore, another type of filtering system must be implemented. One option is to use a standard monochromator with entrance and exit slits replaced by the core of identical fibers, as proposed by lightsource.tech GmbH under reference Monochromator-F.⁷ The bandwidth FWHM (full width at half maximum) of the filtered spectrum, $\Delta\lambda$, is then proportional to the core diameter of these fibers, $2a$, according to the following equation:

$$\Delta\lambda \sim \frac{2a}{Nf} \quad (1)$$

where N is the number of lines per millimeter of the grating and f is the focal length of the monochromator (here, 101.6 mm). Using a 600-lines-per-mm grating leads to a bandwidth of approximately 5 nm for an optical fiber with a 230 μm core diameter, which is ideal for our application. However, the system's overall transmission is problematic: the grating is blazed at 300 nm with a maximum efficiency of about 40% ($\eta_G = 15\%$ at 200 nm), and the monochromator's F-number is 2.7, equivalent to a numerical aperture of 0.18. Consequently, the system's transmission is given by

$$T = \eta_G \times \left(\frac{0.18}{0.22} \right)^2 \approx 0.67 \eta_G \quad (2)$$

and ranges from 10% to 27% depending on the wavelength, compared to 65% for the standard SALSA version, which in addition has a power spectral density of approximately 2 mW/nm. This is why we considered another configuration in which the wavelength tunability of this first filtering stage is discrete rather than continuous. This configuration uses a set of 14 switchable interference filters with a bandwidth between 10 and 40 nm, which

allows complete coverage of the UV spectrum, as illustrated in Fig. 4. Interference filters require a low-divergence beam, which can be obtained by connecting the emission fiber to the focal point of an off-axis parabolic mirror with a UV-enhanced aluminum coating. This discrete configuration will serve as our baseline. The continuous

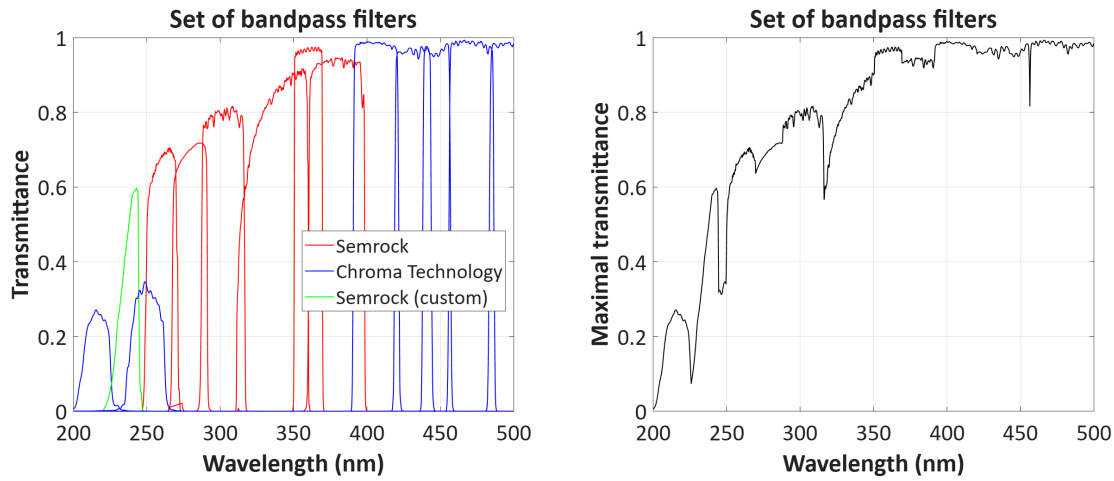


Figure 4. Set of bandpass filters (left, transmission spectrum of all filters; right, effective system transmittance)

configuration will serve as our alternative solution in the event that the relatively large bandwidth of the spectral filtering provided by the discrete configuration causes problems.

The **reference channel**'s structure will be identical to that of the standard SALSA version, except the non-polarizing beamsplitter cube with a 10:90 split ratio will be replaced with a 5° wedge-angled uncoated UV fused silica plate to separate multiple reflections.

The most efficient approach for the **detection module** is to maintain its general structure while adapting key components, such as the mirrors, grating, and detector, to the UV spectrum range. The left graph in Fig. 5 shows the need to replace the mirrors' silver coating with an aluminum/magnesium fluoride coating, which has optimized performance between 200 and 400 nm. The middle graph in Fig. 5 shows the optical design of the KYMERA 193i spectrograph⁸ from Andor, which is identical to that of the SALSA VIS/IR. The right graph in Fig. 5 shows the spectral dependence of the diffraction efficiency of the selected holographic DH grating, which is optimized for the 190-800 nm spectral range.

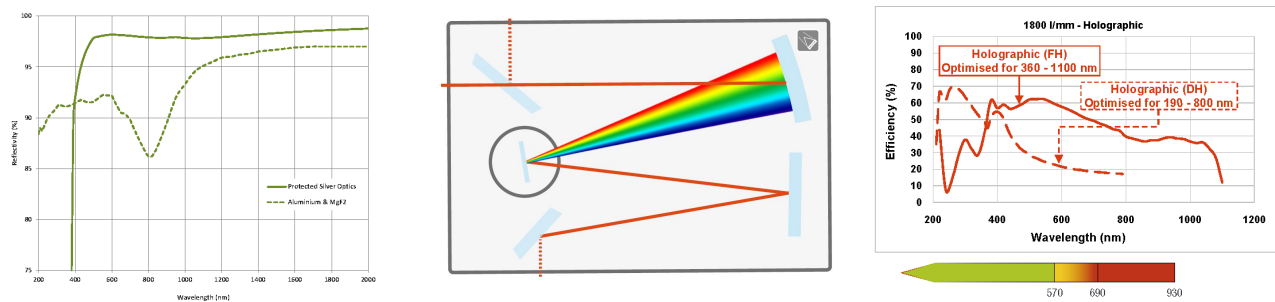


Figure 5. Schematic description of the main features of the spectrograph KYMERA 193i dedicated to SALSA-UV

The detector is similar to the one used in SALSA's visible channel, but its spectral response is optimized for the UV. The Andor IDus 420A-BU2's key specifications are as follows:⁹

- 16-bit back-illuminated CCD array with 1024×255 pixels ($26 \mu\text{m} \times 26 \mu\text{m}$ each)
- Thermoelectrically cooled at -80°C (dark current of $0.002 \text{ e}^-/\text{pixel/s}$)

- Full well capacity of 400,000 e-
- Readout noise of about 10 e- at 100 kHz

3. DESIGN OF THE SOURCE MODULE

Figure 6 shows a 3D representation of the entire source module, with at the left, the fiber version of the laser-driven xenon arc lamp (the link fiber is not shown) followed by a reflective collimator, and two stages of motorized filter wheels. The first stage has a 6-position wheel adapted to 25 mm filter diameter and the second has a 12-position wheel adapted to 12.5 mm filter diameter. The electromechanical shutter is placed at the exit of the

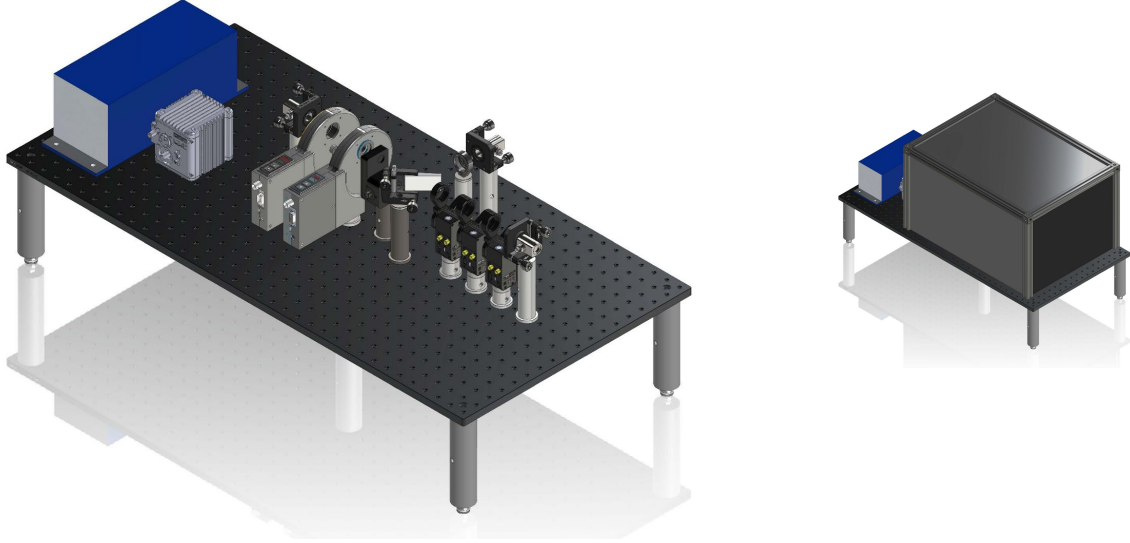


Figure 6. 3D representation of the source module

filter wheels, followed by the uncoated wedge plate that directs a small portion of the light flux toward a silicon photodiode (not shown in the Figure). The majority of the light flux passes through a series of three consecutive optical densities (OD 1, OD 2, and OD 3), each of which is mounted on a motorized flip mount. The prepared light flux, whose wavelength, level, and time duration are now defined, is launched into an optical fiber by an off-axis parabolic mirror. Next to the main drawing in Fig. 6 is a smaller one showing the same source module installed in a black hardboard enclosure to prevent stray light issues.

4. POWER BUDGET

4.1 General Considerations

Figure 7 provides a schematic representation of the results of a functional analysis of the instrument. It shows the different coefficients that drive the power budget.

The power spectral density (PSD $\mathcal{P}$) depends on the fiber's core diameter (115 μm or 230 μm) and wavelength. The quantity T_{OB} is introduced to describe the geometric transmission factor of the optical barrier formed by the transmitter reflective collimator (TRC) and the receiver reflective collimator (RRC). This factor depends on the diameter of the transmitting and receiving fiber cores, as well as the focal length $f = 15$ mm of the two reflective collimators TRC and RRC (see Fig. 1), and the distance between them (1.4 m). This factor only applies to transmission measurements.

Figure 8 shows a schematic representation of the two-dimensional (2D) charge-coupled device (CCD) array with the image of the receiving fiber. This illustrates why the spectral resolution is directly proportional to the core diameter of the fiber and why the amount of light received by each pixel varies inversely with the square of its diameter when identical power is provided by the fiber.

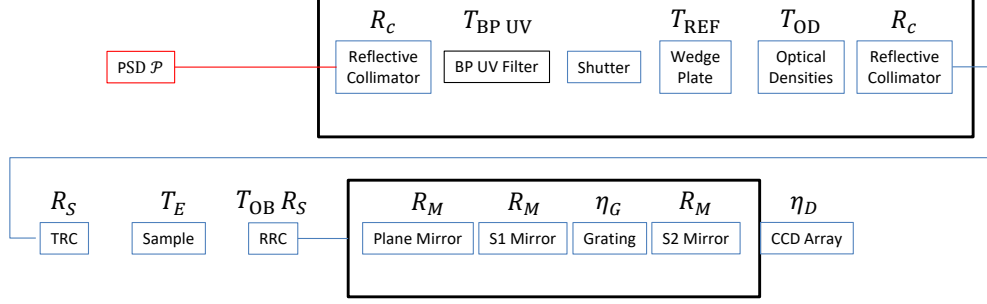


Figure 7. Functional analysis of the instrument

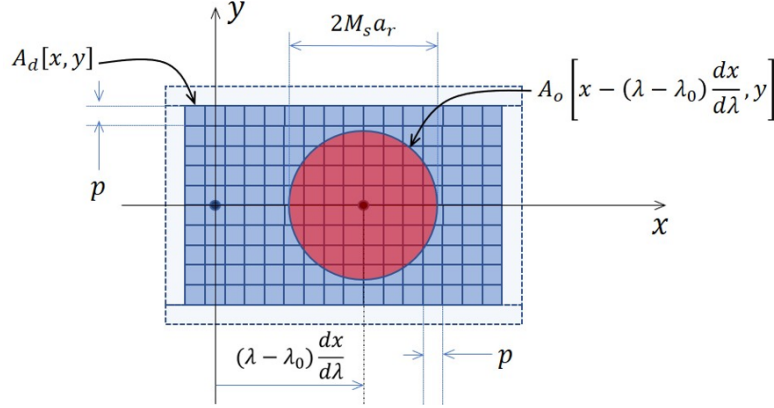


Figure 8. Schematic representation of the CCD focal plane

The signal-to-noise ratio (SNR) of measurements performed by each pixel in the CCD array is defined by the following equation:

$$\text{SNR} = \frac{\bar{m}^2}{\sigma_m^2} = \frac{\bar{m}^2}{\bar{m} + \sigma_{\text{RO}}^2 + \sigma_{\text{DC}}^2} \quad (3)$$

where $\bar{m}$ is the mean number of photoelectrons accumulated in the pixel well, σ_{RO} is the readout noise ($\sigma_{\text{RO}} = 10$ e- @ 100 kHz), and σ_{DC} is the dark current defined by $\sigma_{\text{DC}} = 0.002 \tau$ e- with τ the integration time. Note that the signal-to-noise ratio can be increased by summing the results of measurements taken from all pixels in the same column illuminated by the fiber core.

4.2 Transmission measurements

In transmission mode, the number of photoelectrons accumulated in one pixel of the CCD array located in the image of the receiving fiber core can be calculated using the following three equations:

$$\begin{aligned} \mathcal{P}_D &= \mathcal{P}_s R_c^2 T_{\text{BP UV}} T_{\text{REF}} T_{\text{OD}} R_s^2 T_E T_{\text{OB}} R_M^3 \eta_G \\ E_D &= \frac{\mathcal{P}_D}{\pi (M_s a_r)^2} p \frac{d\lambda}{dx} \\ \bar{m} &= \eta_D \bar{n} = \eta_D \frac{E_D p^2 \tau}{hc/\lambda} \end{aligned} \quad (4)$$

where the meaning of the different coefficients is given in Figs. 7 and 8. Moreover, the detection bandwidth $\Delta\lambda$ and the spectral resolution $\delta\lambda$ are given by:

$$\Delta\lambda = 1024 p \frac{d\lambda}{dx} \quad ; \quad \delta\lambda = 2 M_s a_r \frac{d\lambda}{dx} \quad (5)$$

where M_s is the magnification of the spectrograph ($M_s = 1.07$).

Figure 9 shows the numerical values of the quantities involved in the power budget in transmission mode, as well as the wavelength dependence of the power spectral density for both fiber core diameters and the minimum sample transmission measurable with an SNR of 10. The best performance is achieved with the smallest core diameter (115 μm), due to the optical barrier's better transmission performance with this type of fiber and the increased illumination at the detector's surface.

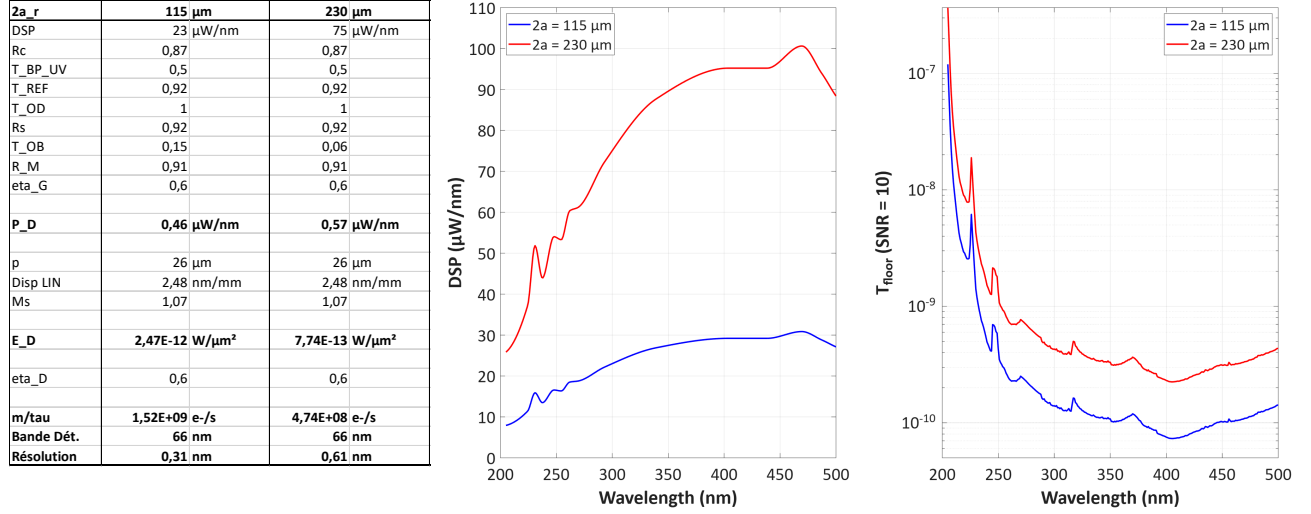


Figure 9. Left: Numerical values of the different quantities at 300 nm - Middle: Spectral dependence of the Power Spectral Density - Right: Wavelength dependence of the minimum sample transmission measurable with an SNR of 10.

4.3 Scattering measurements

The wavelength dependence of the minimum angle resolved scattering (ARS) of a sample measurable with an SNR of 10 is shown in Fig. 10.

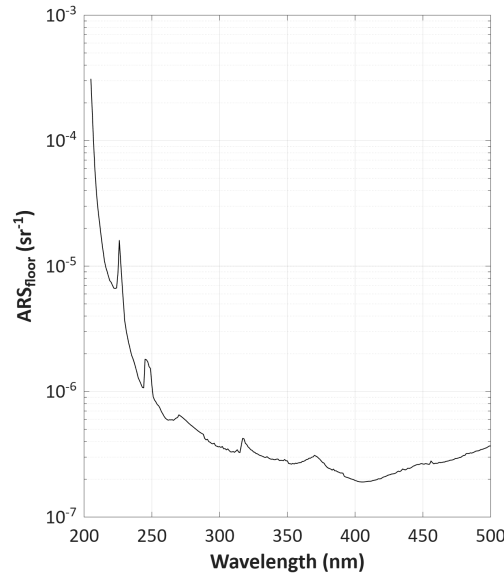


Figure 10. Wavelength dependence of the minimum sample ARS measurable with an SNR of 10.

In this scattering mode, the calculation of detected power $\mathcal{P}_D$ must be adapted using the following equations:

$$\begin{aligned}\mathcal{P}_E &= \mathcal{P}_s R_c^2 T_{\text{BP UV}} T_{\text{REF}} T_{\text{OD}} R_s \\ \text{ARS} &= \frac{1}{\mathcal{P}_E} \frac{d\mathcal{P}_E}{d\Omega} ; d\Omega \approx \pi \frac{a_r^2 + a_t^2}{f^2} \\ \mathcal{P}_D &= R_s R_M^3 \eta_G \text{ARS} \mathcal{P}_E d\Omega\end{aligned}\tag{6}$$

where $d\Omega$ is the solid angle of detection, $2a_t$ is the core diameter of the transmitter fiber, and $2a_r$ is the core diameter of the receiver fiber. f is the focal length of the reflective collimators. In this measurement mode, the best performance is obtained with a 115 μm fiber in emission and a 230 μm fiber in reception.

5. CONCLUSION

The minimum sample transmission measurement achievable with SALSA-UV should be below 10^{-9} across most of the specified spectrum. Under the same conditions, the minimum ARS measurement should be below 10^{-6} sr^{-1} . These values are satisfactory, though they must be confirmed by experimental tests. The oral presentation of this paper will include the first result examples of such experimental measurements.

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REFERENCES

- [1] Liukaityte, S., Lequime, M., Zerrad, M., Begou, T., and Amra, C., "Broadband spectral transmittance measurements of complex thin-film filters with optical densities of up to 12," *Opt. Lett.* **40**, 3225–3228 (Jul 2015).
- [2] Lequime, M., Liukaityte, S., Zerrad, M., and Amra, C., "Ultra-wide-range measurements of thin-film filter optical density over the visible and near-infrared spectrum," *Opt. Express* **23**, 26863–26878 (Oct 2015).
- [3] Zerrad, M., Liukaityte, S., Lequime, M., and Amra, C., "Light scattered by optical coatings: numerical predictions and comparison to experiment for a global analysis," *Appl. Opt.* **55**, 9680–9687 (Dec 2016).
- [4] Lequime, M., Zerrad, M., and Amra, C., "Breakthrough spectrophotometric instrument for the ultra-fine characterization of the spectral transmittance of thin-film optical filters," *Opt. Express* **26**, 34236–34249 (Dec 2018).
- [5] Fouchier, M., Zerrad, M., Lequime, M., and Amra, C., "Wide-range wavelength and angle resolved light scattering measurement setup," *Opt. Lett.* **45**, 2506–2509 (May 2020).
- [6] www.hamamatsu.com/eu/en/product/light-and-radiation-sources/Laser-Driven-Light-Source-LDLS.html.
- [7] [www.lightsource.tech/en/tunable-light-sources/the-monochromator f/](http://www.lightsource.tech/en/tunable-light-sources/the-monochromator-f/).
- [8] [https://andor.oxinst.com/products/kymera-and-shamrock-spectrographs/kymera 193i](https://andor.oxinst.com/products/kymera-and-shamrock-spectrographs/kymera-193i).
- [9] [https://andor.oxinst.com/products/idus-spectroscopy-cameras/idus 420](https://andor.oxinst.com/products/idus-spectroscopy-cameras/idus-420).