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# VUV bandpass reflective coatings for the SMILE-UVI instrument

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## ABSTRACT

The Ultraviolet Imager (UVI) is a challenging instrument developed in the frame of the SMILE mission, a collaboration between ESA and CAS. The UVI instrument is a CMOS-based ultraviolet camera developed to image Earth's northern auroral regions. It is centered on the 160-180 nm UV waveband, with a  $10^\circ \times 10^\circ$  field of view. At the core of the instrument, four thin film-coated mirrors guide light into its detector and ensure most of the signal filtering, crucial to achieve an out-of-band rejection ratio as low as possible to reject light from solar diffusion, dayglow and unwanted atomic lines.

We developed an interferometric coating based on an  $\text{MgF}_2/\text{LaF}_3$  multilayer stack deposited by ion-assisted electron-beam deposition. We gradually improved our evaporation setup to reach a high degree of homogeneity, precision and repeatability on the material thicknesses, over the entire mirrors surface. The reflectivity maximum is above 85% and the wavelength at which it occurs is adjustable within 1 nm, while the out-of-band reflectivity between 120 and 155 nm and between 200 nm and 1100 nm is kept below 6% on average never exceeding 8 %.

The coating has been space qualified and shows stable performances in conditions representative of the instrument operation environment (thermal cycling under vacuum, radiations, UV exposure...).

**Keywords:** SMILE, interferometric coating, VUV, reflective coating, ebeam

## 1. INTRODUCTION

The Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) is a joint ESA-CNSA mission dedicated to the analysis of the interaction between the solar wind and the magnetosphere. The SMILE payload consists of a set of four instruments that measure the most important characteristics of the coupled solar wind - magnetosphere - auroral ionosphere system: the Light Ion Analyzer (LIA), the MAGnetometer (MAG), the soft X-ray Imager (SXI) and the UltraViolet Imager (UVI).

The UVI is an ultraviolet camera to image Earth's northern auroral regions. It will allow to study the connection between the processes taking place in the magnetospheric boundaries – as seen by the SXI – and those acting on the charged particles precipitating into our ionosphere. The UVI consists in a single imaging system based on a four-mirror on-axis optical design and a CMOS sensor coupled with a light intensifier. It features a spatial image resolution at apogee of 150 km and a  $10^\circ \times 10^\circ$  field of view targeting a waveband centered on 160-180 nm, corresponding to a part of the Lyman-Birge-Hopfield (LBH)  $\text{N}_2$  band. Schematics of the optical path followed by the rays entering the instrument is shown in Figure 1.

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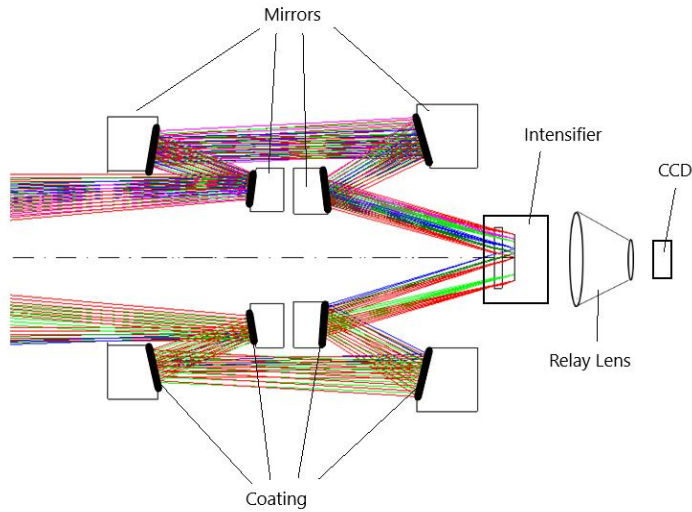


Figure 1: SMILE UVI optical concept.

Since the UVI instrument has to take images of auroras all day around, one of the main technical challenges is to filter out sunlight in the visible range. In order to ensure a sufficient signal-to-noise ratio in the wavelength range of interest, a rejection ratio in the range of  $1E-8$  -  $1E-9$  has to be achieved. While the solar blind nature of the light intensifier accounts for part of the rejection, one of the key elements of the mission is the engineering of a specific coating on the optical surfaces.

The objective of this work is to present the performances of the VUV interferometric reflective coating, based on multilayered thin films, that has been developed and qualified for the UVI instrument to reject light from unwanted atomic lines and solar diffusion.

## 2. MULTILAYER COATING DEVELOPMENT

In order to achieve the required level of performance, we rely mostly on an interferometric coating based on a modified  $\pi$ -multilayer design. Indeed, by carefully choosing the materials and tuning the thin film layers thicknesses, the reflectance peak position and width can be controlled with precision while ensuring a sufficient rejection ratio. In those so-called  $\pi$ -multilayer coatings [1][2], two materials with significantly contrasting refractive indices are stacked in alternation to build the interference. Among the candidate materials,  $MgF_2$  and  $LaF_3$  were selected because they satisfy the refractive index criterion while having low absorption, which preserves the high throughput of the filter coating.



Figure 2: Picture of one of the SMILE UVI mirrors after coating (flight model).

The four SMILE UVI mirrors are made of N-BK7 and are all different. A picture of one of the mirrors is shown in Figure 2. Two of them are concave, while the two other are convex in shape, with outer diameters ranging from 70 mm to 120 mm. The radius of curvature range from 175 mm to 272 mm. The surface roughness is below 0.5 nm RMS on the clear aperture. This value remains below 1.2 nm RMS after coating. Each mirror is coated individually using assisted e-beam evaporation, along with a flat witness sample (N-BK7, 2mm thick, 25 mm diameter) placed at its center that is used for spectroscopic characterization. Previous calibration of the setup ensures the coating is homogeneous on the witness sample and the clear aperture of the mirror. The coating on the mirrors is optimized to work at average incidence angles ranging from  $10^\circ$  to  $22.3^\circ$ .

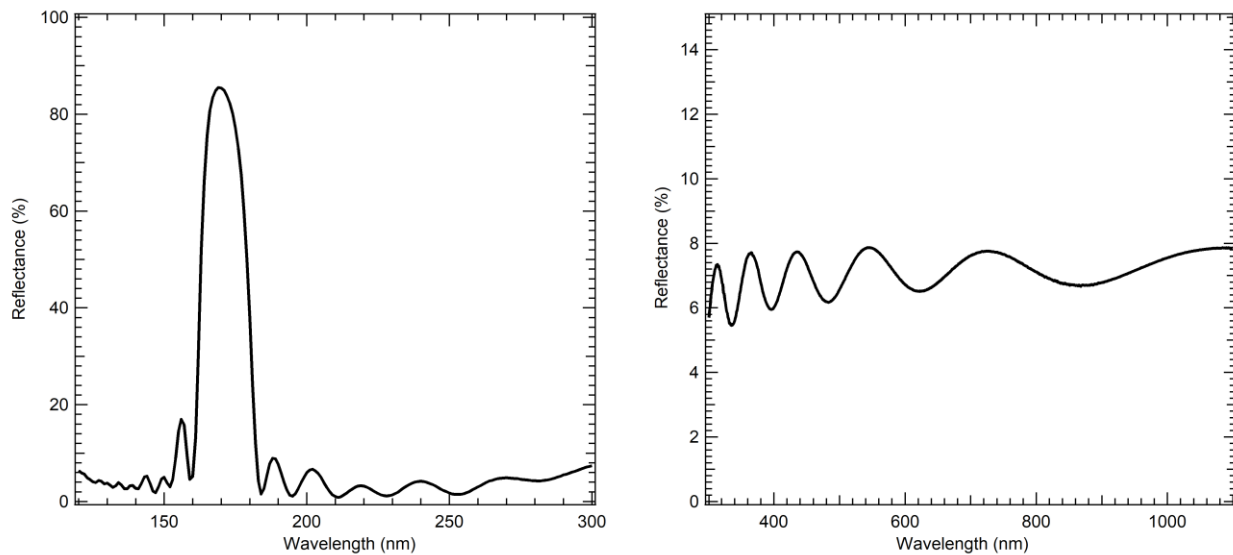


Figure 3: Reflectance at  $10^\circ$  of a coated N-BK7 substrate between 120 nm and 300 nm (left panel) and between 300 nm and 1100 nm (right panel). The contribution of the substrate backside is included in the reflectance.

The reflectance of the coating on a 2 mm-thick N-BK7 substrate is presented in Figure 3 for an angle of  $10^\circ$ . It should be noted that the out-of-band response above 250 nm is increased by a few percents by the reflection on the smooth substrate backside, which is not present on the diffusive mirror backside. Rough estimates of this contribution indicate that it accounts for approximately half of the reflectance value at 400 nm reported in the right panel of Figure 3. The position of the high reflectance peak (above 85%) can be tuned at will with a precision of 1 nm by modifying the

thicknesses of the multilayer thin films. The angular dependence of the reflectance spectra is shown in Figure 4 for three angles relevant for the UVI instrument: 10°, 14° and 23°.

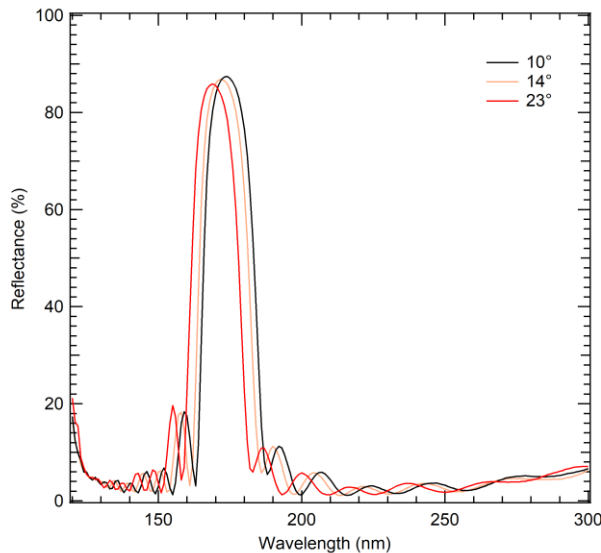


Figure 4: Angular dependence of a coated N-BK7 substrate between 120 nm and 300 nm.

### 3. COATING QUALIFICATION

The coating selected for the SMILE mission has undergone a full qualification campaign, representative of the conditions it will encounter during the mission lifetime. In particular, 12 samples have been prepared and submitted to one or several of the following environmental tests: immersion in solvents, thermal humidity exposure, thermal cycling under vacuum, proton irradiation and UV exposure. The impact of the tests on the coating integrity is assessed by visual inspection of the samples, while the optical performances are evaluated by spectral reflectivity measurements in the wavelengths range of interest (120-1100 nm).

Visual inspections (at X1 and X20) are carried out in reflection using an optical fiber lighting (150 W white light source) over a black background in an ISO 5 clean area. Visual inspections are performed at different steps during the coating qualification campaign, namely before and after each environmental exposure test and spectral reflectivity measurement. The success criteria after exposure are as follows: the sample should remain homogeneous in appearance, i.e., show no discoloration, stains, streaks, smears, or hazy appearance due to intrinsic alteration of the coating, no flaking, peeling, blistering, cracks or delamination.

Reflectivity measurements are carried out using a VUV McPherson spectrometer and a UV-VIS-NIR Lambda 1050 spectrometer from Perkin Elmer, located in an ISO 7 clean room area. Spectral reflectivity is measured before and after each environmental exposure test. The exposure test is deemed successful if there is no degradation of the reflectivity subsequent to the test, within the measurement accuracy of +/-1%, except for proton irradiation, where a 1% degradation is acceptable (so +/-2%).

The immersion test for optical coatings is based on [AD03] (section 4.5.4.2. Solubility and cleanability). It is performed in an ISO 5 clean room area at CSL. The qualification samples are immersed for 10 minutes and in sequence in the following solutions: chloroform, acetone and ethanol. The solvent is allowed to evaporate to dryness without wiping between each solution.

A dedicated programmable climatic chamber from BIA installed in a grey room is used for the humidity resistance tests. The samples are kept for 24 hours at atmospheric pressure, at a temperature of  $45^{\circ}\text{C} \pm 0.3^{\circ}\text{C}$  and a relative humidity of  $93\% \pm 2\%$ , not accounting for the ramp up and down phases, lasting for approximately 10 hours each.

The thermal vacuum cycling (TVAC) test is conducted in a homemade chamber dedicated to the evaluation of optical coating samples according to the ECSS-Q-ST-70-17C Durability testing of coatings [AD01], following procedure [RD08]. The testing chamber is located in an ISO 7 clean area. The temperature and pressure are recorded using a PT-100 thermistor and penning gauge respectively during the whole thermal cycling. The pressure in the chamber is around 1E-6 mbar and 25 cycles are performed, from -87°C to 53°C, with a dwell time of 25 minutes and a heating rate lower than 2°C/min.

The total non-ionizing dose proton irradiation is carried out under vacuum. Samples are irradiated at room temperature with a maximum dose of 70 Mrad and a proton energy of  $10 \pm 0.2$  MeV. The test fluence is  $1.6 \pm 0.2E8$  protons/cm<sup>2</sup>.

The UV exposure facility is based on a Xenon lamp with a spectrum similar to the Sun spectrum. The input beam is filtered to constrain the exposure to wavelengths below 400 nm, in order to reduce the heating of the sample coming from the IR and visible wavelength ranges. Moreover, in order to avoid any “cleaning” effect arising from the oxygen present in the environment, the sample is installed in a vacuum chamber at a pressure of 1E-5 mbar. The total irradiance is 22.5 kcal/cm<sup>2</sup>, corresponding to a sun equivalent time of 101.5 days. In our setup, the acceleration factor is 12, leading to an actual illumination time of approximately 8.5 days.

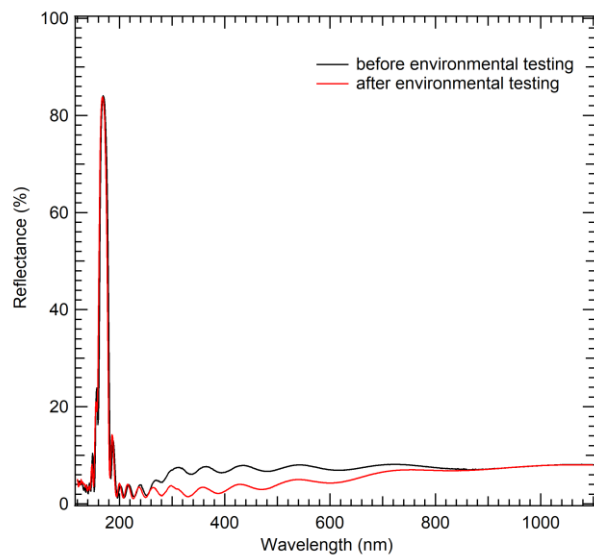


Figure 5: Reflectance at 10° of a coated N-BK7 substrate between 120 nm and 1100 nm right after coating (in black) and after passing through all environmental tests (in red).

Figure 5 shows a comparison of the full reflectance spectra of a qualification sample before and after the whole environmental testing campaign. Besides the impact of the substrate after proton irradiation on the out-of-band coating response, little difference is observed. The coating successfully passed all the qualification tests, although caution should be exerted with humidity exposure, as expected from the presence of hygroscopic materials in the coating. Subsequently to the irradiation test, we noticed a change in the N-BK7 substrate color from transparent to yellow, but without impact on the global performance of the coating.

Finally, an adhesion test is performed in an ISO 5 clean room area according to ISO 9211-4:2012, Conditioning method 2, Adhesion, Degree of severity 01. Degree of severity 01 corresponds to a slow rate tape removal, (2 - 3) s per 25 mm [AD02]. No delamination is observed on the samples and the tape is free of coating.

#### 4. CONCLUSION

As a conclusion, we developed a high throughput reflective coating meeting the challenging filtering requirements of the UVI instrument, in the framework of the SMILE mission. The reflectivity maximum is above 85% and the wavelength at which it occurs can be tuned within 1 nm, while keeping the out-of-band reflectance below 6% on average. This interferometric coating has been qualified for the environmental conditions encountered by the SMILE satellite.

## ACKNOWLEDGEMENTS

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