

Dielectric Broadband Mirror Coating for Space Applications

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ABSTRACT

Broadband reflective optics are essential components of spaceborne imaging spectrometers used for Earth observation and environmental monitoring. Instruments such as TROPOMI on Sentinel-5P [1], GOME-2 on MetOp [2], and FLORIS on FLEX [3] rely on mirrors that provide high reflectance over wide spectral ranges while maintaining optical figure and environmental robustness. Conventional metallic coatings remain the standard solution for such optics, but their intrinsic material limitations restrict achievable reflectance and spectral coverage, particularly in the ultraviolet. This work investigates dielectric broadband mirrors as a competitive alternative for space applications, with the aim of matching or surpassing metallic performance while preserving the mechanical and environmental stability required for deployment in orbit.

Four use cases were defined, including three mission-oriented cases derived from ESA-related instruments, together covering multiple spectral regions in the range from 240 to 2500 nm and one generic case covering the spectral range from 340 to 1040 nm. The coatings were designed for high reflectivity > 98 % at angles of incidence (AOI) between 0° and 25° and deposited by ion beam sputtering (IBS). Spherical concave shaped fused silica and Zerodur mirrors with diameters of 125 mm and 120 mm were developed, manufactured and tested, including thermal vacuum and climate chamber testing. This work presents the design, development and manufacturing of these dielectric broadband optical coatings

Keywords: Dielectric broadband mirror coating, IBS

1. INTRODUCTION

Metallic reflector coatings have extensive flight heritage in European Earth-observation instrumentation. ESA's SCIAMACHY imaging spectrometer on Envisat (2002–2012), for example, employed aluminum scan-mirror surfaces across a 240–2385 nm spectral range; in-flight measurements subsequently revealed wavelength-, scan-angle- and polarization-dependent throughput changes associated with contamination of the oxidized aluminum surfaces [4]. The operational Copernicus Sentinel-3 SLSTR instruments use silver-coated Zerodur telescope mirrors [5], while the hyperspectral EnMAP instrument incorporates eleven metal mirrors, with protected-silver coatings for the visible range and sputtered-gold coatings for infrared applications. These implementations illustrate the principal attraction of metals: broad spectral coverage with comparatively moderate sensitivity to incidence angle.

However, for photon-starved imaging spectrometers, the finite absorption of metallic layers is a fundamental limitation, because the reflectance losses of successive telescope and spectrometer mirrors accumulate multiplicatively. Silver provides excellent VIS–IR reflectance but exhibits a pronounced short-wavelength decrease below approximately 400 nm and requires adhesion and protective layers. Imperfections in these layers can initiate corrosion or interfacial transport, while the protection itself may reduce reflectance [6].

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Aluminum extends farther into the UV, but native oxidation, contamination and charged-particle exposure can introduce spectrally dependent loss and time-dependent polarization effects [4,7]. Such changes increase calibration complexity and may ultimately affect radiometric stability. All-dielectric multilayer mirrors could therefore provide substantially higher reflectivity and lower absorption over a suitably defined near-UV/VIS/NIR band, improving end-to-end throughput, signal-to-noise ratio and thermal stability. Dense oxide stacks may additionally eliminate the corrosion-prone metallic layer and offer high environmental durability.

The work presented here examines the potential for using dielectric-coated broadband mirrors as an alternative to conventional metallic mirrors in future space missions. Three typical application scenarios in ESA missions (TROPOMI on Sentinel-5P, GOME-2 on MetOp, and FLORIS on FLEX) and a generic broadband application scenario were defined as use cases for development. For these four cases, highly reflective dielectric broadband coatings covering the near UV, VIS and near IR spectral range were developed, deposited in IBS coating processes on spherically concave mirror substrates made of fused silica and Zerodur and characterized on their performance. Their resistance to environmental stresses was tested in thermal-vacuum and climate chamber tests, as well as in adhesion and abrasion tests. Figure 1 shows a comparison of the reflectivity of typical metallic coatings with the reflectivity requirements for the four selected use cases.

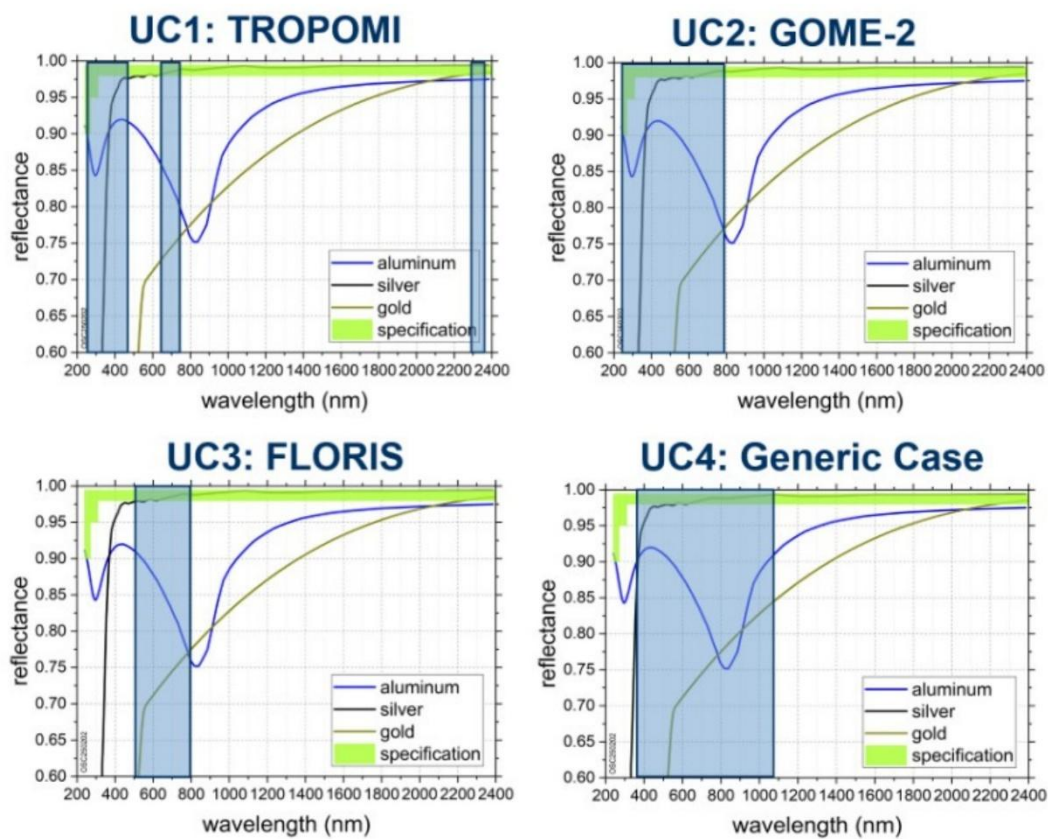


Figure 1. Comparison of the reflectivity of typical metallic coatings (aluminum, silver, and gold) with the reflectivity requirements for the developed dielectric broadband mirror coatings of the use cases. The green band in each graph indicates the tolerance range for the required reflectivity, while the blue-shaded areas define the spectral ranges for the respective use case summarized in Table 1.

2. COATING DESIGN AND MANUFACTURING

Several classes of coating materials can be applied in different spectral ranges, but for the visual spectral range with the adjacent UV- and IR ranges, oxides are the preferred choice due to their good transparency and well-established deposition processes. Typically, two materials, one with a high and one with a low index of refraction, are selected. The low-index material is usually SiO₂, while the high-index material is one of several possible metal oxides, mostly TiO₂, Ta₂O₅, or HfO₂.

The refractive index, in combination with the absorptive losses of each material, limits the bandwidth and spectral range that can be achieved with mirror coatings. A high refractive index difference between high and low index material is preferred for a large-bandwidth mirror but high index materials usually cause higher absorption in the UV. On the other hand, materials that are more transparent in UV tend to feature a lower refractive index. This is a fundamental limitation of all optical coatings. To mitigate this and to achieve the necessary combination of both high bandwidth and high reflectivity in the developed coating designs, two materials are not enough to fulfil the desired specifications. Therefore, multi-material designs are required to combine two separate high-index materials in three of the four use cases (1, 2, and 4). The materials chosen are TiO₂ and HfO₂. TiO₂ features a high refractive index of $n > 2.2$ ($\lambda = 632$ nm) and high transparency down to 400 nm. HfO₂, in contrast, has a refractive index of $n < 2$ ($\lambda = 632$ nm), but high transparency down to approximately 260 nm. Table 1 summarizes the coating materials used and the specifications for coating designs.

Table 1. Coating materials and coating specifications.

Use Case	Coating Materials	Coating Specification
All		$R > 95\%$ for $240\text{ nm} \leq \lambda < 310\text{ nm}$, $R > 98\%$ for $\lambda > 310\text{ nm}$, AOI = $0 - 25^\circ$
1	HfO ₂ , SiO ₂ , TiO ₂	Range: 270–500 nm (range 1) + 675–775 nm (range 2) + 2305–2385 nm (range 3) Reflectivity variation: $\Delta R = \pm 0.5\%$ all three ranges Coating layers: 158, thickness: 14.2 μm
2	HfO ₂ , SiO ₂ , TiO ₂	Range: 240–790 nm Reflectivity variation: $\Delta R = \pm 1\%$ ($\lambda < 310\text{ nm}$), $\Delta R = \pm 0.5\%$ ($\lambda \geq 310\text{ nm}$) Coating layers: 76, thickness: 4.3 μm
3	Ta ₂ O ₅ , SiO ₂	Range: 500–780 nm Reflectivity variation: $\Delta R = \pm 0.25\%$ Coating layers: 59, thickness: 5.6 μm
4	HfO ₂ , SiO ₂ , TiO ₂	Range: 340–1040 nm Reflectivity variation: $\Delta R = \pm 0.5\%$ Coating layers: 78, thickness: 5.5 μm

All developed coatings were produced using the Ion-Beam Sputtering (IBS) coating process on two coating machines operated at the LZH (Laser Zentrum Hannover e.V.). The IBS process was chosen for its high manufacturing precision in coating thickness and the high environmental stability of the produced coatings. Both coating machines were selected to produce different material combinations, one machine for two-material coating layer stacks, and one for three-material coating layer stacks. Figure 2 shows the coating machines used for the presented work. For layer thickness control, the LZH-developed optical broadband monitor (BBM) was used. Monitoring was performed from 400 nm up to 1700 nm, and the monitoring substrates were exchanged during deposition, depending on the thickness of the final coating of each use case. A series of process optimization and prototype coating runs were performed before manufacturing the final demonstrator mirror coatings.

To demonstrate the manufacturing processes and characterize the developed dielectric broadband coatings, the coating systems were deposited on spherically concave mirror substrates made of Zerodur ($\varnothing 120 \times 15$ mm, RoC: -557 mm) and fused silica ($\varnothing 125 \times 15.6$ mm, RoC: -550 mm), as well as on Zerodur and fused silica witness samples ($\varnothing 50.8 \times 6.5$ mm, $\varnothing 25.4 \times 3$ mm, and $\varnothing 25.4 \times 1$ mm).

Figure 3 shows the manufactured spherically concave Zerodur demonstrator mirror substrates. To counteract the wavefront deformation of the optic introduced by the compressive coating stress, all mirrors and witness samples were provided with a stress compensating coating on the back side.



Figure 2. The IBS machines used for coating deposition. The machine in panel A uses a custom ion source, a classical rotating substrate holder, and can accommodate up to four different coating materials. This machine manufactured all three-material coating layer stacks for the use cases 1, 2, and 4. The machine presented in panel B features a 16 cm Veeco source, a planetary rotation, and can accommodate two coating materials. This machine manufactured two-material coating layer stacks for use case 3.

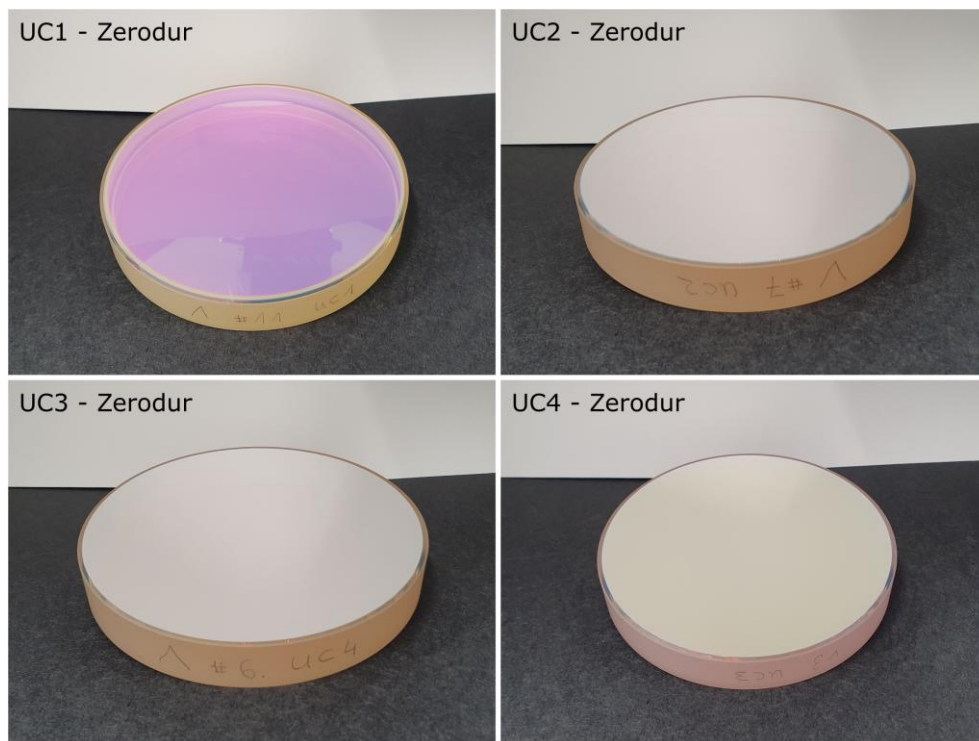


Figure 3. During prototype and demonstrator development, spherically concave mirror substrates made of Zerodur ($\varnothing 120 \times 15$ mm, RoC: -557 mm) and fused silica ($\varnothing 125 \times 15.6$ mm, RoC: -550 mm) were coated with the coating layer stacks developed for the four use cases. This figure shows the coated Zerodur mirror substrates.

3. MIRROR PERFORMANCE

To characterize the coated mirrors, their reflectivity was measured in the specified spectral range after coating, as well as before and after thermal-vacuum and climate chamber testing. The reflectivity was measured in the angular range AOI = 0–25°. Figure 4 shows the spectral characterization of all coatings compared to the respective design and the tolerance band for reflectivity. Figure 5 shows the reflectivity of the developed coatings in the angular range AOI = 0–25°.

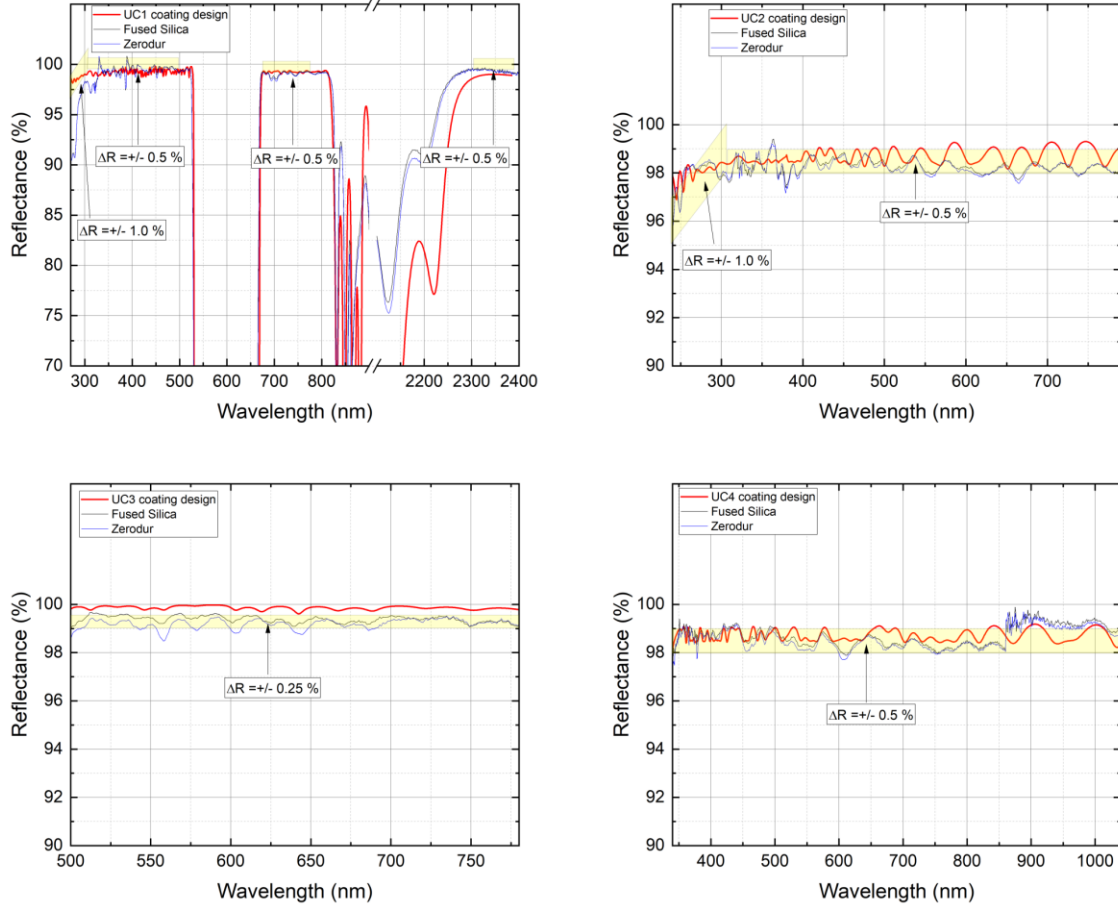


Figure 4. Comparison of the reflectivity measured at AOI = 8° (black = fused silica, blue = Zerodur) with the design (red) for all use cases, as well as the reflectivity tolerance range. For use cases 2, 3, and 4, the measured reflectivity falls within the specified, blue-shaded tolerance band, with only minor, tightly confined deviations. Use case 1 shows a slight deviation from the tolerance band in the near-UV range, which can be further reduced through additional optimization of the process parameters.

Total scattering of the developed broadband dielectric coatings was determined at a wavelength of 532 nm using the method standardized in ISO 13969. Table 2 summarizes the measured total scattering. It covers a range from 257 ppm (UC2 / fused silica) to 1980 ppm (UC1 / Zerodur). It should be noted that the portion of incident light that is neither reflected nor absorbed by the coating layer stack penetrates the bulk material and, in the case of Zerodur, leads to an increase in scattering caused by the mirror material.

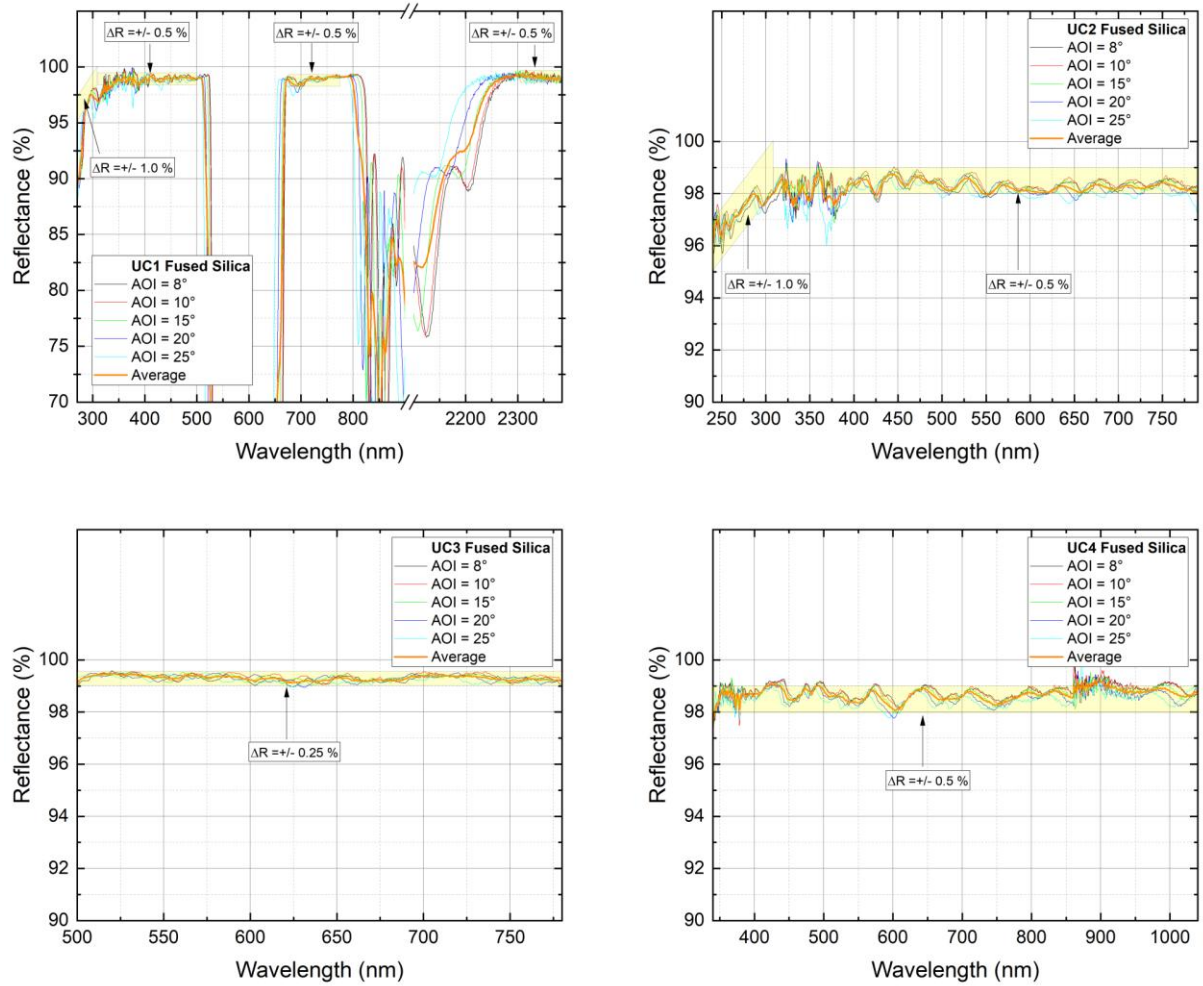


Figure 5. Measured reflectivity for all use cases (fused silica witness samples) at AOI = 8°, 10°, 15°, 20°, and 25°.

Table 2. Total scattering at $\lambda = 532$ nm for all use cases and mirror materials.

Use Case / Substrate	Total Scattering $\lambda = 532$ nm (ISO 13969)
UC1 / fused silica	550 ppm
UC1 / Zerodur	1980 ppm
UC2 / fused silica	257 ppm
UC2 / Zerodur	918 ppm
UC3 / fused silica	683 ppm
UC3 / Zerodur	1420 ppm
UC4 / fused silica	612 ppm
UC4 / Zerodur	1000 ppm

The absorption of the coated mirror substrates was determined using laser calorimetric absorption measurements in accordance with ISO 11551:2019 at wavelengths of 355 nm, 532 nm, and 750 nm, depending on the use case. The measured absorption ranges from 91 ppm (UC 2 / Fused Silica) to 1.07% (UC 1 / Zerodur), depending on the wavelength and use case.

Table 3 summarizes the measured absorption values. When interpreting these values, it should be noted that TiO₂ layers deeper within the coating system effectively absorb unreflected light in the near-UV spectral range. All coated Zerodur mirrors exhibit higher absorption than identically coated fused silica mirrors, as unreflected light is absorbed to a greater extent by Zerodur compared to fused silica.

To characterize potential performance changes due to environmental stress, a thermal vacuum test (-30 °C to +60 °C, 100 cycles, qualification level, per ECSS-E-ST-10-03-Rev 1) and a climate chamber test (T = 45 °C, H_{rel} = 95%, duration = 7 days), as well as abrasion and adhesion tests (ISO 9211-4:2006, Grade 1) have been performed with witness samples for all use cases and both mirror materials.

In the thermal vacuum test, demonstrator mirrors for each use case and both mirror materials were tested in addition to the witness samples. Spectral characterization measurements show no changes following the thermal vacuum (TV) and climate chamber tests. Figure 6 shows a comparison of the UC 4 mirror reflectance before and after the TV test. Inspection of the samples revealed no visible coating damage or delamination after any of these four environmental stress tests.

Table 3. Absorption values measured using laser calorimetric absorption measurements in accordance with ISO 11551:2019. Depending on the use case, absorption measurements were performed at wavelengths $\lambda = 355$ nm, $\lambda = 532$ nm, and $\lambda = 750$ nm and range from 91 ppm (use case 2) in the near-IR to 1.07 % in the near-UV (use case 1).

Coating Absorption			
Wavelength	355 nm	532 nm	750 nm
Use case 1 (ranges: $\lambda = 270 - 500$ nm + $\lambda = 675 - 775$ nm + $\lambda = 2305 - 2385$ nm)			
Fused Silica	0.99 %	Not applicable	580 ppm
Zerodur	1.07 %	Not applicable	0.19 %
Use case 2 (range: $\lambda = 240 - 790$ nm)			
Fused Silica	0.98 %	651 ppm	91 ppm
Zerodur	0.83 %	0.52 %	0.13 %
Use case 3 (range: $\lambda = 500 - 780$ nm)			
Fused Silica	Not applicable	0.2 %	485 ppm
Zerodur	Not applicable	0.11 %	111 ppm
Use case 4 (range: $\lambda = 340 - 1040$ nm)			
Fused Silica	0.62 %	771 ppm	110 ppm
Zerodur	0.68 %	0.34 %	0.1 %

To compensate for stress introduced into the mirror substrates by the coating process, all mirrors (witness samples and spherically concave demonstrator mirrors) were coated on both sides. Since the coating systems developed for the study presented here are not optimized for a specific instrument, the mirrors were coated identically on both sides to evaluate the potential for stress reduction through a compensatory coating deposited on the mirrors back surface. In the event of instrument-specific further development, the back-side coating can be adjusted. The goal of the development was to achieve an increase in the wavefront error (WFE) value of < 5 nm rms induced by the coating process. Two demonstrator mirrors were manufactured for each use case and mirror material. Of the total of 16 mirrors, 15 were measured interferometrically with a DynaFiz 4" (Zygo) interferometer at ESTEC (ESA), both before and after coating (including the back-side coating). Four of the 15 mirrors showed an increase in the WFE value of < 5 nm rms after coating was completed; eight of the 15 mirrors showed a reduction in the WFE value after coating (-6 to -21 nm rms); and three of the 15 showed

an increase of more than 5 nm rms (5–20 nm rms). To mitigate the observed changes in WFE caused by the coating process, future development should include heat treatment of the mirror substrates prior to the coating process, combined with a subsequent interferometric inspection, as part of the manufacturing process. The mirror substrates used for the presented development were not heat-treated between the polishing and coating processes.

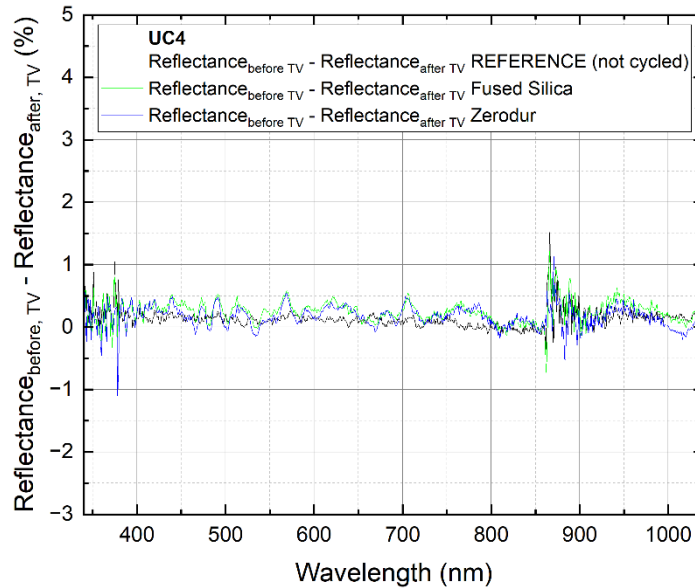


Figure 6. This figure shows the reflectance for Zerodur and fused silica witness sample measured before and after TV testing and not cycled reference witness sample.

4. CONCLUSION AND OUTLOOK

Broadband mirrors used in optical instruments on ESA space missions are typically coated with metallic coatings. Within the scope of this work, dielectric broadband mirror coatings were developed, manufactured, and tested, whose spectral bandwidth and high reflectivity are tailored to the requirements of instruments on ESA missions.

In addition to three dielectric broadband mirror coating designs adapted to three past ESA missions (TROPOMI on Sentinel-5P, GOME-2 on MetOp, FLORIS on FLEX), a fourth dielectric broadband mirror coating design was developed, manufactured, and tested that is conceived as a general use case with a broad spectral range spanning from the near UV to the near IR. This approach opens the possibility of using UC 4 for as many space-based optical instruments, yet to be defined, that require mirrors for a broad spectral range.

To evaluate the performance of the developed dielectric broadband mirror coatings, demonstrator mirrors with spherical curvature made from two substrate materials (fused silica and Zerodur) were coated. The size of the coated mirrors is Ø 125 mm (fused silica, ROC = -550 mm) and Ø 120 mm (Zerodur, ROC = -557 mm), respectively. The spectral characteristics (reflectance), coating absorption and scatter, coating defects, coating-induced changes in wavefront error, and the influence of a thermal-vacuum and climate-chamber test on the optical performance and coating adhesion (via adhesion and abrasion tests) of the optical coatings were measured.

The tests carried out on the four developed dielectric broadband coatings show that dielectric broadband coatings have great potential for use in space-based optical instruments and have the potential to outperform classic metallic coatings. The developed coatings exhibited no observable degradation after thermal-vacuum testing, climate-chamber testing, or adhesion and abrasion testing. Irradiation tests were not performed as part of this work. All developed coatings were coated on two coating machines operated at LZH.

The measurements show that the developed dielectric broadband mirror coatings, particularly in the near-UV spectral range, allow a significant increase in reflectivity compared to metal coatings. In contrast to metallic coatings, dielectric coatings also offer the possibility of tailoring the spectral properties in selected wavelength ranges specifically to the requirements of the instrument in which they are used. Further performance optimizations can be implemented in the developed dielectric broadband coatings, provided that detailed and instrument-specific requirements are considered in the development process.

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