

Flight hardware for the LSTM VNIR/SWIR optics: characterization of IPF, DPF and dichroic flight parts and reconstructed combined performance

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ABSTRACT

The Copernicus Land Surface Temperature Monitoring (LSTM) mission will provide field-scale observations of land-surface temperature and evapotranspiration in support of agricultural water management, drought assessment and climate adaptation. The VNIR/SWIR optical chain of the LSTM instrument realizes six spectral channels between 490 nm and 1610 nm by distributing the filtering function over several coated elements: an intermediate plane filter unit (IPF) with stripe filters and a wedged lens shapes the bandpass, detector plane filter units (DPF-VIS, DPF-SWIR) provide out-of-band rejection and crosstalk suppression, and a dichroic beam splitter separates the VIS and NIR/SWIR branches. Materion Balzers Optics is responsible for these optical elements and, beyond the coated parts, for the DPF and IPF filter assemblies, with Airbus Defence & Space as customer and Fraunhofer IOF as subcontractor for the mechanical parts, integration and testing. This paper reports on the flight hardware: all DPF-VIS and DPF-SWIR flight assemblies and the first IPF flight model have been delivered to Airbus DS, two further IPF models are under test, two dichroic flight models have been delivered, and the dichroic flight spare has been manufactured and tested. The combined spectral response of the DPF and IPF flight optics is presented for all channels, reconstructed from component-level spectral measurements, together with homogeneity mapping and wavefront results of the dichroic flight hardware and the lessons learned from flight production.

Keywords: coating, PARMS, bandpass filter, dichroic, flight model, homogeneity, LSTM instrument, Copernicus

1. INTRODUCTION

LSTM is one of the six Copernicus Sentinel Expansion missions. Its two satellites will carry a thermal-infrared radiometer complemented by visible/near-infrared (VNIR) and short-wave infrared (SWIR) channels, mapping land-surface temperature at field scale every one to two days [1], [2]. The derived evapotranspiration products address the needs of the agricultural user community in a world of growing water scarcity. They further serve applications such as drought prediction, coastal and inland water management and the monitoring of urban heat islands. Airbus Defence & Space in Spain is the mission prime, while the instrument is developed and produced by Airbus Defence & Space in Toulouse [3], [4]. The first satellite is planned to be launched in 2028 [1].

In the VNIR/SWIR branch of the instrument, the spectral definition of the six channels listed in Table 1 is not performed by a single filter. It is shared between three coated elements in the optical path. The intermediate plane filter unit (IPF) is located close to the dichroic, consists of large stripe filters and a wedged lens element and is responsible for shaping the bandpass. The dichroic plate divides the beam into the VIS and the NIR/SWIR paths. In front of each detector, a detector plane filter unit (DPF-VIS or DPF-SWIR) with smaller stripe filters completes the out-of-band rejection and suppresses crosstalk between adjacent channels. The IPF works with high-F-number beams at small angles of incidence, whereas the DPF units see low-F-number beams over a wide angular range. This must be considered in every coating design. The VNIR-3 band is implemented at two stripe positions, denoted VNIR-3a and VNIR-3b.

Table 1. VNIR/SWIR spectral channels of the LSTM instrument.

Channel	Central wavelength [nm]	FWHM [nm]	Focal plane
VNIR-0	490	65	VIS
VNIR-1	665	30	VIS

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Channel	Central wavelength [nm]	FWHM [nm]	Focal plane
VNIR-2	865	20	VIS
VNIR-3a / VNIR-3b	945	20	NIR/SWIR
SWIR-1	1380	30	NIR/SWIR
SWIR-2	1610	90	NIR/SWIR

Materion Balzers Optics (MBO) in Jena is responsible to Airbus DS for all coated VNIR/SWIR elements – the IPF and DPF stripe filters, the IPF lens and the dichroic beam splitter (VNDBS) – and, beyond the optical elements, for the complete DPF-VIS, DPF-SWIR and IPF filter assemblies. The manufacturing of the mechanical frames, the integration of the stripes and the environmental testing of the assemblies are performed by Fraunhofer IOF as subcontractor to MBO [7], [8]. Earlier ICSO contributions described the optical design, the deposition technology, the manufacturing approach and first characterization results of the coated elements [5], [6]. The present contribution concentrates on the flight hardware itself: the manufacturing and characterization of the flight filter stripes and lens, the reconstructed combined spectral performance of the DPF and IPF flight optics, and the homogeneity and wavefront verification of the dichroic flight parts. The measured properties are presented and discussed with respect to the design expectations.

2. FLIGHT HARDWARE AND PROJECT STATUS

The filter assemblies follow a model philosophy consisting of a development model for the coating and dicing processes, a mechanically representative model serving the TRL 6 demonstration of the assembly design [8], and two flight models per assembly type. In addition, a spare was manufactured for the IPF. For the dichroic, a development model, an engineering model, two flight models and a flight spare have been manufactured. The status in September 2026 is summarized in Table 2. Photographs of the coated optical components (Figure 1), of the DPF assemblies (Figure 2) and of the IPF assembly at two integration stages (Figure 3) are given below; the dichroic flight model FM2 is shown in Figure 4.

Table 2. Status of the LSTM VNIR/SWIR flight hardware manufactured by MBO (September 2026).

Element	Flight models	Status
DPF-VIS filter assembly	PFM, FM2	Integrated, tested and delivered to Airbus DS
DPF-SWIR filter assembly	PFM, FM2	Integrated, tested and delivered to Airbus DS
IPF filter assembly (stripes and lens)	FM1	Integrated, tested and delivered to Airbus DS
IPF filter assembly (stripes and lens)	FM2, spare	Assembled; environmental and optical testing ongoing
Dichroic beam splitter (VNDBS)	FM1, FM2	Manufactured, tested and delivered to Airbus DS
Dichroic beam splitter (VNDBS)	Flight spare	Manufactured and tested; delivery review pending

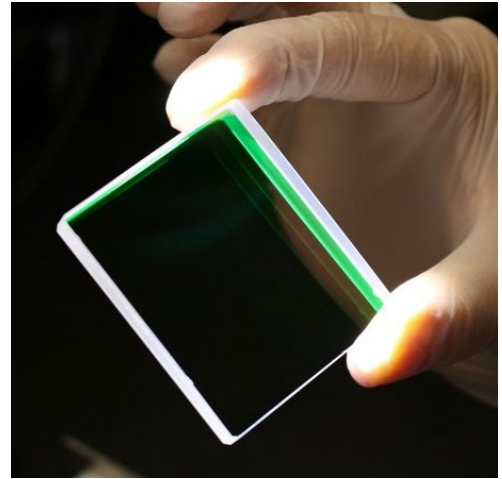
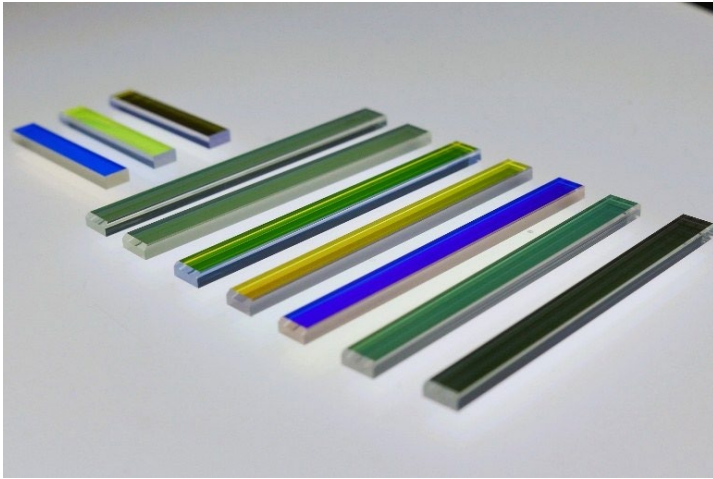


Figure 1. Coated optical components: IPF and DPF-VIS filter stripes after dicing (left) and IPF lens (right).

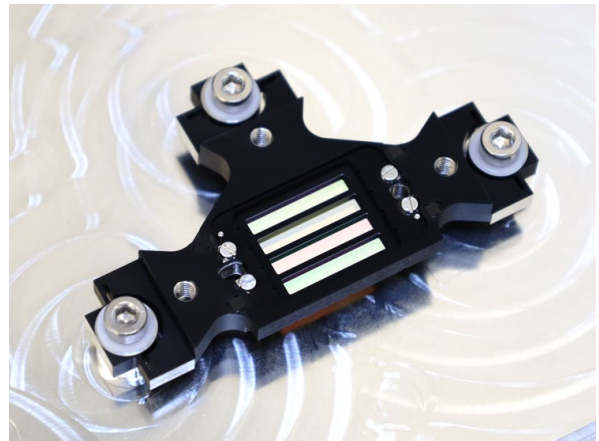
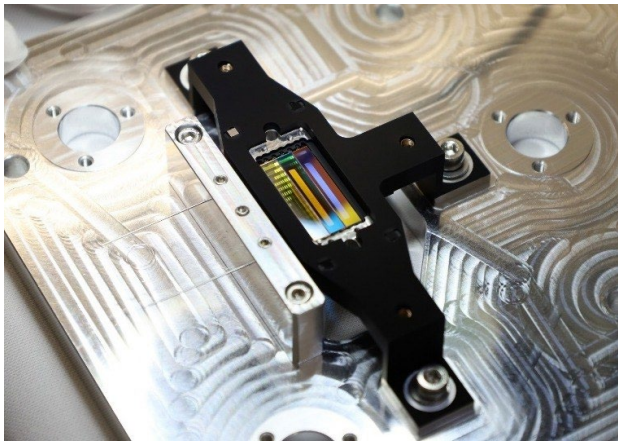


Figure 2. Detector plane filter assemblies: DPF-VIS FM1 with the stripes integrated into the lower frame, before mounting of the upper frame (left), and DPF-SWIR flight model FM2 before packing for delivery (right).

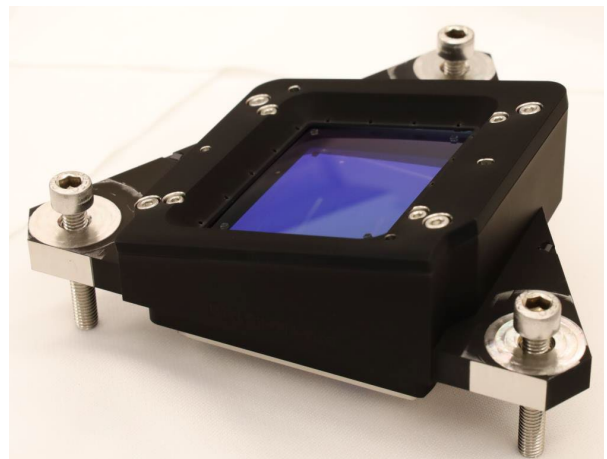
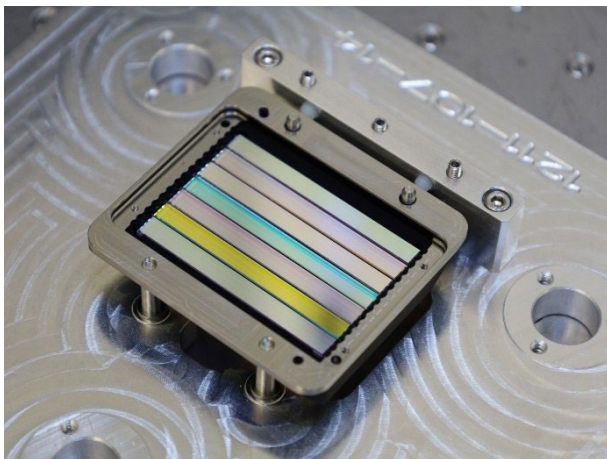


Figure 3. Left: IPF filter stripes integrated into the frame, before mounting of the cover frame and the lens. Right: IPF flight model FM1

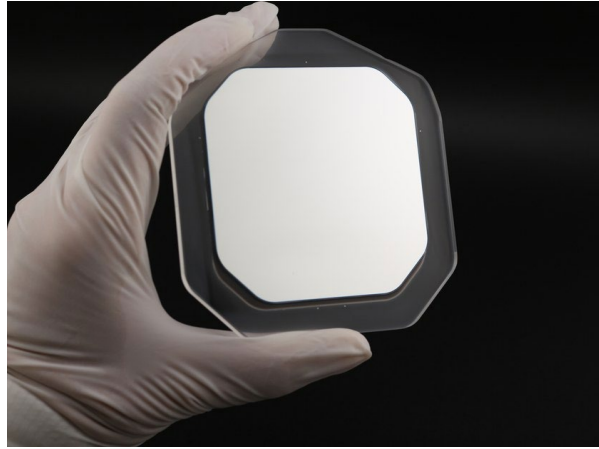


Figure 4. Dichroic beam splitter flight model FM2 before delivery.

3. COATING DESIGN AND MANUFACTURING APPROACH

3.1 Filter stripes and lens

All coatings are deposited by plasma-assisted reactive magnetron sputtering (PARMS) on Helios plants (Bühler). These plants are equipped with optical broadband monitoring, which measures the optical thickness of the growing layer stack directly on the rotating substrate holder and enables in-situ correction of the individual layers [9], [10]. The bandpass and blocking filters are realized as $\text{SiO}_2/\text{Ta}_2\text{O}_5$ layer stacks on Corning HPFS 7979 fused-silica substrates. The choice of PARMS was driven by the total coating thickness required for the specified rejection and bandpass shape, which exceeds the practical limit of ion-assisted evaporation. A second reason was the homogeneity and process reproducibility already demonstrated in the Sentinel-2 [12] and 3MI [13] heritage of MBO.

For each channel the spectral function is distributed over six coated surfaces – two on the IPF stripe, two on the IPF lens and two on the DPF stripe. The number of different coating designs was deliberately kept small: the IPF stripe carries the bandpass design on side 1, while the IPF side 2 and the DPF side 1 share one blocking design, and the DPF side 2 carries a second blocking design. The lens is coated with two designs that are common to all channels. In this way, qualified and stable deposition processes are reused several times. Table 3 lists the resulting physical coating thickness per element. The thickest stacks are required for SWIR-1, where the steep bandpass edges relative to the 30 nm bandwidth and the very broad blocking range lead to almost 50 μm of total dielectric material deposited on the IPF stripe.

Table 3. Total physical coating thickness (both sides) of the flight designs per channel.

Channel	IPF stripe [μm]	DPF stripe [μm]	Coating materials
VNIR-0	15.8	13.0	$\text{SiO}_2 / \text{Ta}_2\text{O}_5$
VNIR-1	17.3	15.5	$\text{SiO}_2 / \text{Ta}_2\text{O}_5$
VNIR-2	19.9	11.9	$\text{SiO}_2 / \text{Ta}_2\text{O}_5$
VNIR-3a/b	30.7	32.9	$\text{SiO}_2 / \text{Ta}_2\text{O}_5$
SWIR-1	49.2	41.2	$\text{SiO}_2 / \text{Ta}_2\text{O}_5$
SWIR-2	30.9	22.7	$\text{SiO}_2 / \text{Ta}_2\text{O}_5$

The coatings are deposited on Ø100 mm fused-silica wafers, which are subsequently diced into individual stripes with a chip saw. The stripes are characterized individually and selected for integration based on their spectral, geometrical and cosmetic properties. Here, the main challenge for flight production was achieving the required combination of properties

on the same stripe. The IPF lens, a wedged fused-silica element with one plane and one spherical surface, is coated in separate runs with the two common lens designs.

3.2 Dichroic beam splitter

The design of the dichroic plate (VNDBS) was fixed during the pre-development phase [5]: a 176-layer Nb₂O₅/SiO₂ stack with a physical thickness of 14.8 µm on a fused-silica wedge plate, deposited on a Helios 800 plant, combined with an anti-reflection coating on the rear side. The spectral edge between reflection and transmission separates the VIS channels from the NIR/SWIR channels. Both the steepness of the edge and its lateral uniformity over the useful optical area are therefore essential for the spectral performance of the instrument. The design allows for a homogeneity of ±0.3 % of the edge position over the useful aperture to fulfill the spectral specification.

4. CHARACTERIZATION OF THE FLIGHT FILTER STRIPES AND LENS

4.1 Filter stripes

Every stripe foreseen for a flight model is characterized individually. Blocking and polarization properties, which require larger apertures, are measured on the coated wafers before dicing. After dicing, the spectral transmittance is measured at three positions along each stripe with PerkinElmer Lambda 950/1050 double-monochromator spectrophotometers. Length and width are checked with an optical edge-detection system. The thickness is calculated from the wafer thickness measured before coating and the coating thickness known from the deposition process and is expressed as equivalent fused-silica thickness. Surface imperfections are inspected on every stripe according to ISO 10110-7 [11], both for the full clear aperture and for sub-pupils.

The transmitted wavefront error of the wafers is measured interferometrically before coating. Since the coated filters are opaque at the interferometer wavelength of 632.8 nm, the transmitted wavefront error of the coated stripes is estimated from reflected wavefront measurements on both sides of representative stripes of each batch. The power terms of the two sides add up, while the sum of the irregularity terms gives an upper bound for the transmitted irregularity. Micro-roughness is measured by atomic force microscopy on representative samples. The total integrated scattering (TIS) in transmission is measured on wafer level for the flight coating batches. Table 4 summarizes the methods and results; Figure 5 shows the TIS measurements of the DPF flight wafers.

Table 4. Non-spectral characterization of the DPF and IPF flight stripes – results for the characterized stripes and representative samples.

Parameter	Method	Result
Stripe thickness (equivalent fused silica)	Wafer thickness before coating plus coating thickness	DPF: 2002–2009 µm; IPF: 2006–2019 µm (all flight stripes)
Stripe length and width	Individual dimensional inspection by optical edge detection	measurement accuracy ±6 µm (DPF) and ±10 µm (IPF)
Surface imperfections	Visual inspection per ISO 10110-7 on full aperture and sub-pupils	defect maps recorded for every stripe; flight stripes selected on this basis
Estimated transmitted WFE (ISO 10110 13/A, 13/B)	Reflected WFE on both sides (Zygo GPI, 632.8 nm) of representative stripes, combined as described above	13/A: 0.5–105 nm; 13/B: 45–307 nm
Micro-roughness	AFM on representative coated samples	0.27–0.85 nm rms
Total integrated scattering	TIS in transmission on wafer level, flight coating batches	low in-band scattering, see Figure 5 for the DPF wafers

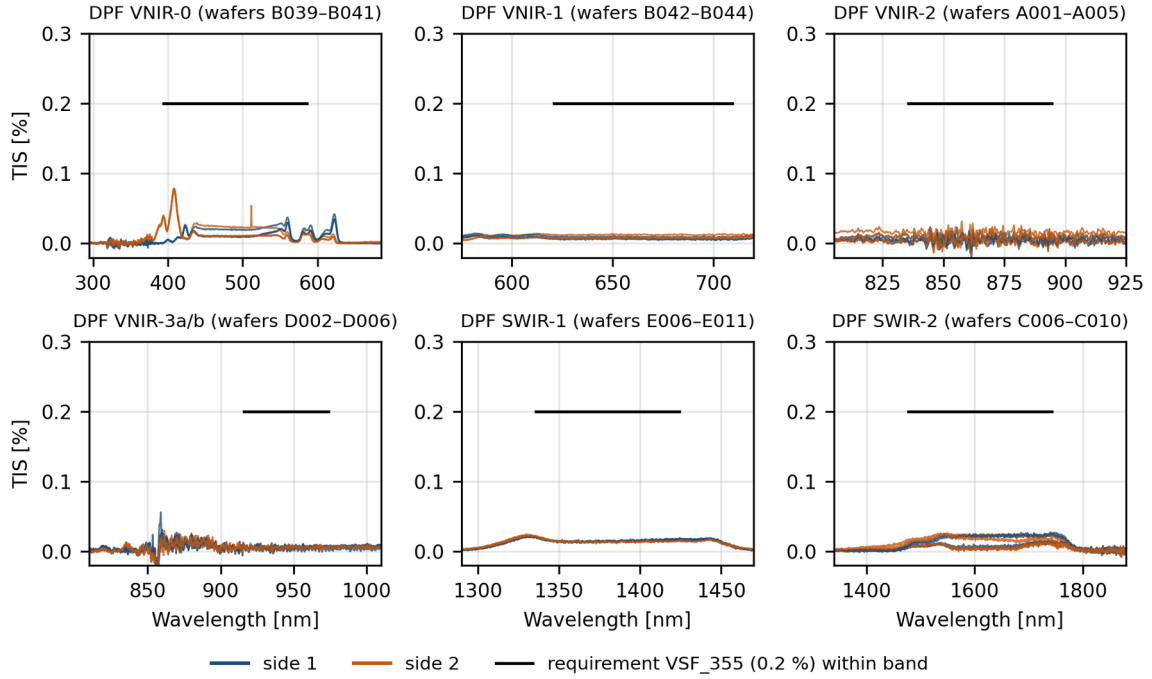


Figure 5. Total integrated scattering (transmission) measured on the DPF flight coating batches for both coated sides. The black bars mark the 0.2 % level within the respective spectral band

The estimated wavefront values of the representative stripes are consistent with the error budget established at design level. They characterize unmounted stripes; the wavefront performance of the mounted assemblies is verified at assembly level [8]. The coated representative samples show rms roughness values of 0.27–0.85 nm, and the in-band scattering of the DPF flight wafers is low, as illustrated in Figure 5.

4.2 IPF lens

The IPF lens is a 53 mm × 44.5 mm wedged fused-silica lens with one plane and one spherical surface, procured polished and coated at MBO with the two common lens designs. Several lenses were coated in the flight batch. The geometry and the surface form of both faces are verified by the lens supplier before coating. The uncoated lens surfaces have 3/A values of 43–62 nm and 3/B values of 63–107 nm. The spectral performance of the lens coatings was characterized spectrophotometrically and by an integrating-sphere transmittance measurement on the coated lens at normal incidence between 300 nm and 2500 nm. The total integrated scattering of the lens coatings is 0.01–0.04 % in the six spectral bands. For the VNIR-2 example, the lens contributes a high, nearly flat in-band transmittance, as shown in Figure 6.

5. COMBINED SPECTRAL PERFORMANCE OF THE FLIGHT OPTICS

5.1 Evaluation approach

The spectral requirements of the mounted filters are defined for the chain of IPF stripe, IPF lens and DPF stripe, for three illumination scenarios described by histograms of the angle of incidence (center, minimum and maximum field of view). In the earlier publications, the combined response could only be evaluated by merging measured IPF stripes with the design data of the lens and of the DPF stripes [5], [6]. With all flight elements now available, the total transmittance of each channel is reconstructed from measured data only. For every angular histogram, the histogram-weighted transmittance spectra of the IPF stripe, of the lens coatings and of the DPF stripe are multiplied wavelength by wavelength. Each stripe is measured at three positions along its length, and the spectral results of these positions are combined. This gives a direct impression of the spread caused by the residual spectral inhomogeneity along the stripes.

The combined curves are evaluated with the same figures of merit that were used in the design analysis: the centroid wavelength and the full width, both weighted with the spectral detector efficiency, the in-band and edge templates, the out-

of-band transmittance against the blocking target, the in-band transmittance and ripple of the DPF, and the polarization contrast. The measurement uncertainty of the spectrophotometers is taken into account by tightening the evaluation criteria by twice the standard deviation of the measurement, i.e. wavelength positions by 0.3 nm and transmittance levels by 0.7 % of the nominal value. These guard bands cover the instrument uncertainty and are not a full propagation of the uncertainty of the reconstructed chain. The analysis presented here combines the DPF stripes of the proto-flight models with the IPF stripes and the lens of the IPF flight model FM1.

5.2 Results

Figure 6 illustrates the approach for the VNIR-2 channel: the bandpass is entirely shaped by the IPF stripe, while the lens and the DPF stripe contribute a nearly flat in-band transmittance close to 100 %. The resulting reconstructed total transmittance for the three angular scenarios is compared with the spectral template in Figure 7. The peak transmittance of the complete chain is above 97 % and the shift between the center and the extreme field-of-view scenarios amounts to roughly 1 nm, in line with the design prediction. Figure 8 shows the reconstructed out-of-band blocking of a representative channel against the blocking target.

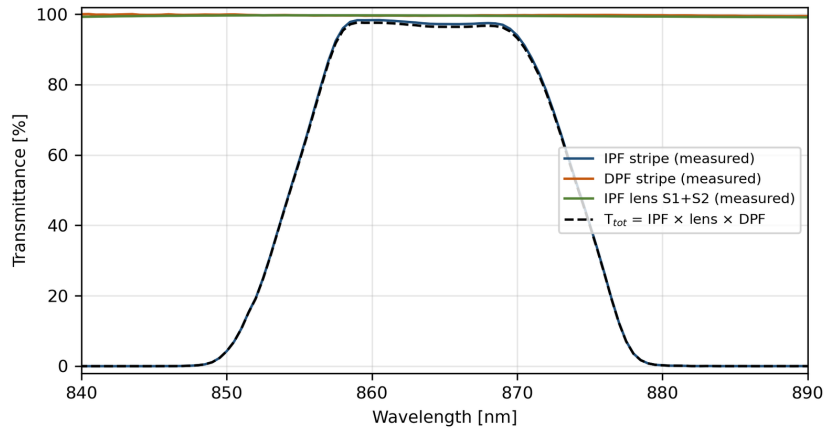


Figure 6. Measured transmittance of the VNIR-2 flight elements – IPF stripe, lens coatings (both sides) and DPF stripe – for the center-field histogram and the resulting reconstructed total transmittance of the chain.

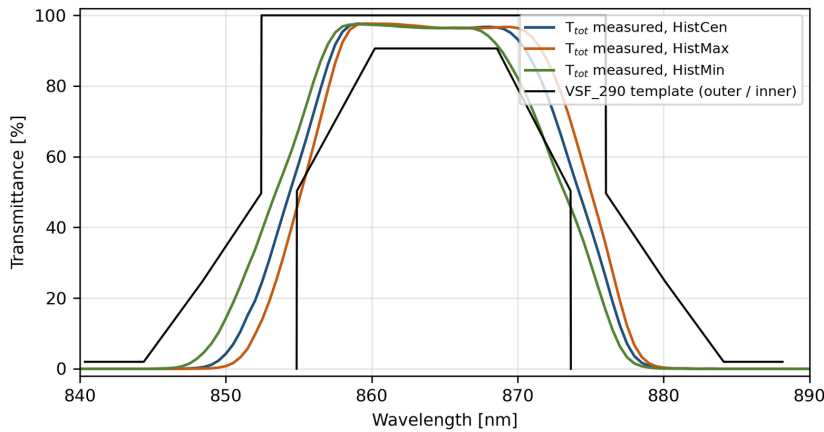


Figure 7. Reconstructed combined transmittance of the VNIR-2 flight optics (IPF stripe $\times$ lens $\times$ DPF stripe) for the three angle-of-incidence histograms, shown against the outer and inner boundaries of the spectral template of the center-field scenario; the evaluation uses the scenario-specific template for each histogram.

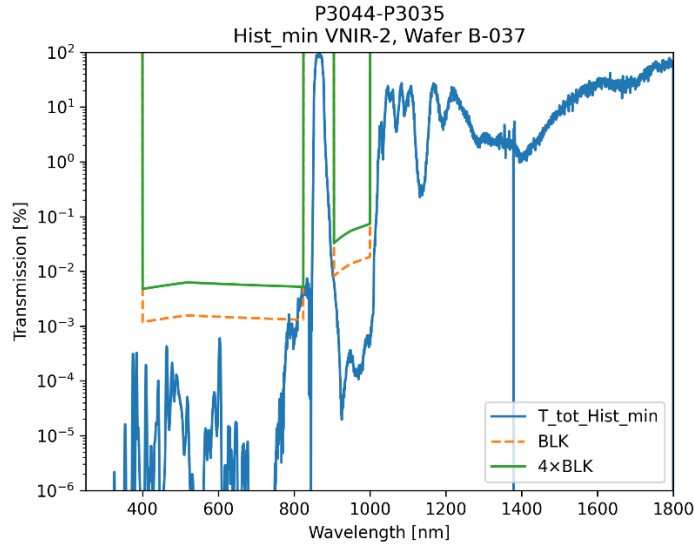


Figure 8. Reconstructed out-of-band blocking of the flight optics of the FM1 VNIR-2 channel compared with the blocking target.

Table 5 compares the centroid wavelength and the full width at half maximum obtained for the center-field histogram – given as the range over the measured stripe positions – with the values predicted by the coating design, and lists the average in-band transmittance of the DPF stripes. The measured centroids lie below the design prediction for most channels, with VNIR-0 showing a small positive offset. The largest offset amounts to about 0.3 % of the center wavelength, and the bandwidths agree with the design within 0.6 nm. The spread across the measured positions is below 0.4 nm for the VNIR channels and about 1 nm for the SWIR channels, confirming that the selected stripes are spectrally uniform along their length. The DPF stripes transmit between 98.9 % and 99.7 % in band, and the reconstructed out-of-band transmittance stays well below the blocking target for all channels. Differences between measurement and design remain within the range identified in the design analysis and were assessed together with Airbus DS with respect to the instrument performance. Examples are the polarization contrast of the wide VNIR-0 channel and the flank position for the minimum-field scenario of some channels.

Table 5. Reconstructed combined spectral performance of the DPF and IPF flight optics for the center-field histogram: design prediction versus measurement (range over the measured stripe positions).

Channel	Centroid design [nm]	Centroid measured [nm]	FWHM design [nm]	FWHM measured [nm]	DPF in-band transmittance
VNIR-0	488.8	489.4–489.7	63.1	63.2–63.3	99.5–99.6 %
VNIR-1	665.6	664.0–664.2	29.5	29.4	99.3 %
VNIR-2	866.4	864.0–864.2	20.0	20.2	99.6–99.7 %
VNIR-3a	946.3	943.7–944.0	20.8	20.6	99.5–99.6 %
VNIR-3b	946.5	945.3–945.6	20.8	20.5	99.5–99.6 %
SWIR-1	1381.7	1379.7–1380.4	29.5	28.9–29.0	99.4–99.5 %
SWIR-2	1612.9	1607.8–1608.8	89.9	89.7	98.9–99.3 %

6. DICHROIC FLIGHT HARDWARE

Figure 9 gives an overview of the measured reflectance of the dichroic side over the VNIR/SWIR range: the three VIS channels are reflected at close to 100 %, and the NIR/SWIR channels fall into the transmitted region beyond the steep edge. The filter stripes provide additional out-of-band rejection in the respective optical paths. The curves for the different angles of incidence illustrate the small angular shift of the edge that the design was optimized for [5].

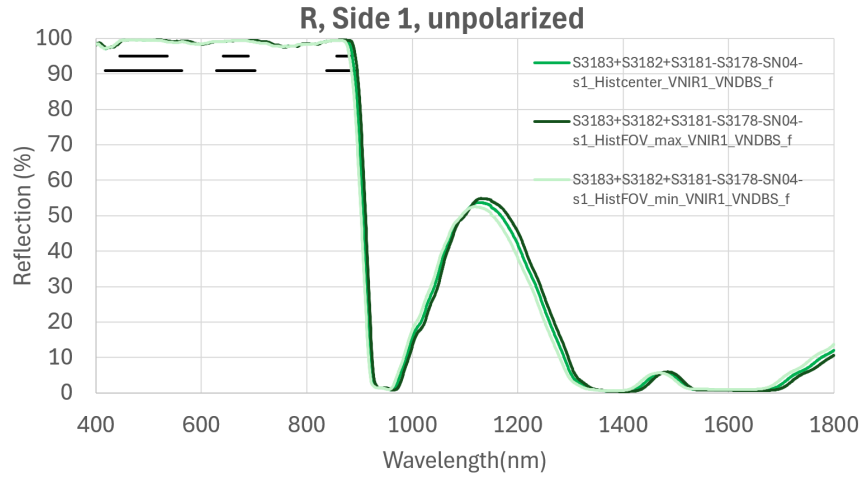


Figure 9. FM2 - measured reflectance of the dichroic side of the flight hardware (unpolarized) for three angles of incidence; the short horizontal bars indicate the positions of the three VIS channels.

6.1 Homogeneity mapping

The spectral properties of the dichroic are relevant over the complete useful optical area and for angle-of-incidence histograms. The lateral distribution of the spectral edge over the aperture therefore enters directly into the performance assessment. For every dichroic model, the position of the 50 % transmittance point of the edge was mapped at normal incidence over a dense grid covering the useful area, complemented by line scans across the transition zone at the aperture boundary (Figure 10). The variation of the edge position over the useful area turned out to be larger than the $\pm 0.3\%$ allowed for in the design, which makes the homogeneity the dominant contributor to the spectral verification of the part.

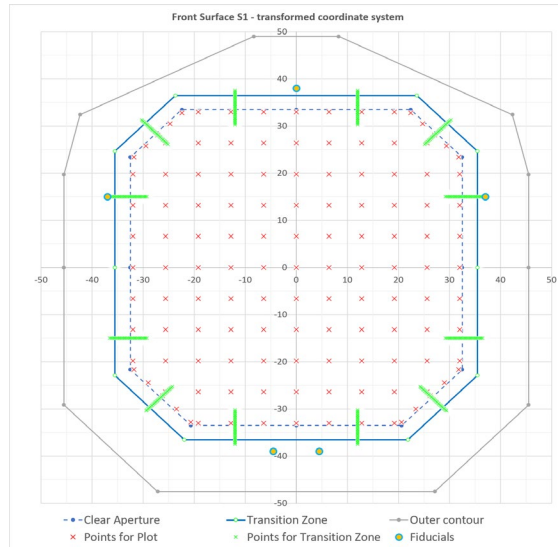


Figure 10. Measurement positions used for the homogeneity mapping of the dichroic: grid points within the clear aperture and line scans across the transition zone.

The spectral verification of each dichroic is based on a center measurement of reflectance and transmittance for s- and p-polarization at 8° and from 16° to 48° . Two parameters enter the evaluation: the weighting of the data according to the specified incidence histograms, and the distribution of the spectral performance over the clear aperture taken from the homogeneity map of the part. In this way, the histogram-weighted evaluation covers the complete useful area. For the flight spare, the unshifted, histogram-weighted evaluation over the specified core spectral bands gives an average

reflectance of the dichroic side of approximately 98.7–99.9 % in the three VIS bands and an average transmittance of approximately 98.0–99.4 % in the NIR/SWIR bands over the three angular histograms. The anti-reflection side shows a reflectance of 0.3–2.1 %. The influence of residual inhomogeneity on the combined spectral performance was assessed together with Airbus DS using histogram-weighted spectral data.

6.2 Wavefront error

The reflected wavefront error of the coated parts is measured at MBO with a Zygo interferometer. The transmitted wavefront error after coating was measured by an external laboratory at 970 nm on the engineering model and on fully representative verification parts of both flight models. The results are compiled in Table 6 together with the hardware to which they refer.

Table 6. Optical characterization results of the dichroic flight hardware and the hardware to which they refer.

Parameter	Method	Hardware	Result
Average reflectance of dichroic side, VIS bands	histogram-weighted s/p measurement, 8°–48°, three angular histograms	flight spare	≈ 98.7–99.9 %
Average transmittance, NIR/SWIR bands	histogram-weighted s/p measurement, three angular histograms	flight spare	≈ 98.0–99.4 %
Reflectance of anti-reflection side	histogram-weighted s/p measurement, three angular histograms	flight spare	0.3–2.1 %
Reflected wavefront error (rms irregularity)	Zygo GPI, 632.8 nm, instrument reference frame	flight spare	12.5 nm
Transmitted wavefront error (rms), coated	external laboratory, 970 nm	EM / verification parts of FM1 and FM2	16.2 / 20.9 / 44.0 nm

6.3 Lessons learned

The dichroic turned out to be the most demanding element of the LSTM VNIR/SWIR optics. The reason is not its spectral design, but the homogeneity required over a large aperture in combination with angle-of-incidence histograms and a spectral edge located close to narrow channels. Full-aperture mappings revealed edge-position variations that are not represented by a center measurement alone. Uniformity control and its interaction with the angular illumination conditions were therefore key considerations in flight production. A second lesson concerns the part geometry: the uniformity masking of the deposition is constrained by the space available around the clear aperture, and an earlier agreement on the mechanical outline of the dichroic would have allowed a more effective masking and a better homogeneity. For future developments of comparable dichroics, an early agreement with the customer on the part geometry and on how histogram-weighted requirements are verified over the aperture is therefore recommended.

7. CONCLUSION

With the delivery of all DPF-VIS and DPF-SWIR flight assemblies, the first IPF flight model and both dichroic flight models, the LSTM VNIR/SWIR optics developed by Materion Balzers Optics have reached flight status. Flight production has demonstrated the successful manufacturing and characterization of the complex dielectric coatings, with up to 50 µm of dielectric material on a single IPF stripe. The combined spectral response of the filter chain – IPF stripe, lens and DPF stripe – has now been reconstructed entirely from measured data of the flight production. The results follow the design prediction for centroid wavelength, bandwidth and blocking of all six channels closely. The dichroic flight parts show excellent spectral performance in the center of the aperture but revealed the coating homogeneity over the large aperture as the main technical challenge of the program. The next steps are the delivery of the dichroic flight spare, the completion of the IPF FM2 and spare test campaign and the support of the integration and performance verification at instrument level by Airbus DS.

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