

Design, Manufacturing and Characterization of a Large-Aperture Polarization Scrambler for the Hyperspectral Imaging Spectrometer (HIS) of the TRUTHS Satellite Mission.

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Abstract

The Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS) mission was conceived to provide SI-traceable radiometric reference measurements with unprecedented accuracy for long-term climate monitoring. To meet the stringent radiometric requirements of the hyperspectral imaging spectrometer (HIS), polarization-dependent errors introduced by dispersive and refractive optical elements must be effectively mitigated. This paper presents the design, manufacturing, and experimental characterization of a large-aperture polarization scrambler based on a Dual Babinet Pseudo Depolarizer (DBPD). The proposed depolarizer consists of two optically bonded Babinet compensators fabricated from crystalline quartz, with the second pair rotated by 45° with respect to the first one. This configuration introduces spatially varying polarization-dependent phase delays across the beam, thereby reducing the degree of polarization at the output. The manufacturing process, including precision fabrication, crystal-axis alignment, and subsequent surface correction, is described with respect to the demanding requirements of the TRUTHS HIS instrument. The depolarization performance was experimentally evaluated using intensity modulation measurements with rotating polarizers and camera-based detection, while spot separation measurements were used to assess the wedge-angle accuracy and the diamond effect. The results show a substantial reduction in the degree of polarization and good agreement with design expectations and simulations, confirming the suitability of the DBPD concept for high-accuracy spaceborne hyperspectral imaging systems.

Keywords: TRUTHS mission, hyperspectral imaging spectrometer, polarization scrambler, depolarizer, Dual Babinet Pseudo Depolarizer, birefringent wedges, degree of polarization, diamond effect.

1 Introduction

Prior to the withdrawal of UK funding, which led to the suspension of its development, the Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS) mission was intended to serve as the “gold standard” for climate change monitoring. The mission was designed to generate SI-traceable reference datasets of unprecedented quality and accuracy for space-based Earth observation systems, aiming to reduce measurement uncertainties and ensure long-term temporal consistency, even beyond the operational lifetime of individual instruments. The primary observational instrument of the TRUTHS mission is a hyperspectral imaging spectrometer (HIS) [1].

To mitigate polarization bias and satisfy stringent accuracy requirements, a polarization scrambler was incorporated into the HIS design. A Dual Babinet Pseudo Depolarizer (DBPD) placed before the slit of HIS was selected as the optimal solution [2]. Such component is essential in modern imaging spectrometers, which are inherently sensitive to the polarization state of incoming radiation due to the presence of dispersive and refractive optical elements. Variations in the incident polarization can introduce systematic radiometric errors, potentially compromising the precision of retrieved measurements. Polarization scramblers (or depolarizers) address this limitation by transforming a well-defined input polarization state into a distribution of polarization states, such that the detected signal becomes effectively unpolarized. In practice, this is achieved using birefringent optical elements that introduce polarization-dependent phase delays varying across the beam cross-section, leading to an averaging of the Stokes parameters and a significant reduction in polarization sensitivity [3]. While earlier spaceborne instruments relied on dedicated polarization measurement subsystems, modern designs favor passive depolarization solutions due to their simplicity and efficiency, making polarization scramblers a critical enabling technology for high-accuracy Earth observation missions [4, 5].

In this paper, we describe the design of the TRUTHS HIS depolarizer, the manufacturing process developed to meet its stringent uncertainty requirements, and the experimental characterization performed to assess and validate the performance of the developed element.

2 Design and requirements

The Dual Babinet Pseudo Depolarizer selected for the TRUTHS mission consists of four prisms fabricated from a birefringent material. Its function is to depolarize arbitrary input polarization states by introducing spatially varying phase delays across the pupil. This results in a superposition of different polarization states at the output, such that the emerging beam can be considered effectively unpolarized.

The optical design is based on two pairs of wedges with different wedge angles. Within each pair, the prisms are bonded with their crystal axes oriented orthogonally to each other and to the optical axis, thereby forming an equivalent plane-parallel plate, i.e. a single Babinet compensator. The dual Babinet configuration is achieved by rotating the second pair by 45° about the optical axis with respect to the first pair and bonding both pairs together [2, 6].

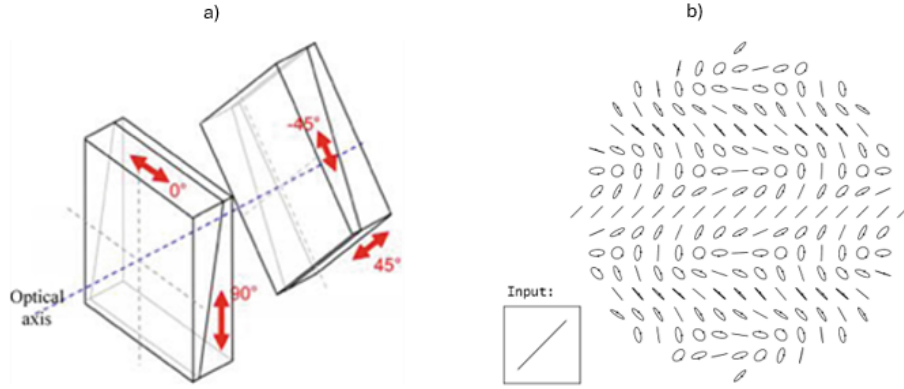


Figure 1: (a) Schematic principle of a Dual Babinet Pseudo Depolarizer (DBPD) [2]. (b) Polarization pupil map at the last surface of the depolarizer.

In addition to depolarization, birefringence introduces image degradation in the form of modulation transfer function (MTF) reduction, commonly referred to as the “diamond effect”. Each prism produces a beam deviation determined by its wedge angle and the incident polarization state. For the four-prism configuration, this results in the formation of four spatially separated images.

The depolarizer aperture in the proposed design is circular, with a diameter of 60 ± 0.5 mm and a clear aperture of 50 mm. The central thickness of each wedge is specified as 3 ± 0.03 mm, with wedge angles of $12 \pm 0.01^\circ$ and $18 \pm 0.01^\circ$, respectively, to limit the “diamond effect”. Finalized outer optical surfaces are required to meet a surface form tolerance of 3/1(1) fringes, a scratch-dig specification of 20–10, and a microroughness of 0.7 nm or better, in accordance with ISO 10110. The angular alignment between the crystal axes within each pair is set to $90 \pm 1^\circ$, while the relative orientation between the two pairs is defined as $45 \pm 1^\circ$.

The material selected for the depolarizer wedges is crystalline quartz (X-cut), with an ordinary refractive index of $n_o = 1.5443$ and an extraordinary refractive index of $n_e = 1.5534$. Optical bonding is achieved using UV-cured NOA-61 adhesive, which has established space heritage.

3 Manufacturing

Based on the customer requirements, the standard manufacturing drawings for all the individual plates, for both individual Babinet sub-assemblies and the final dual-Babinet depolarizer were realized. The drawings are non-trivial as we are dealing with the birefringent material and they need to reflect also manufacturing and measurement processes. The Figure 2 shows the final element with the required optical performance.

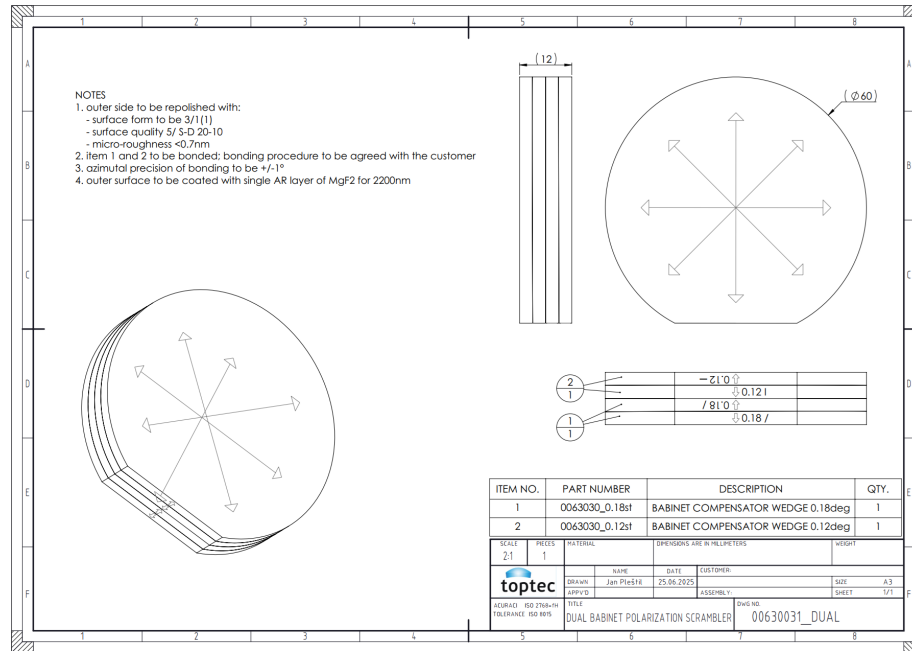


Figure 2: Manufacturing drawing of the final dual-Babinet polarization scrambler.

3.1 Crystal axis orientation and plate referencing

As we are dealing with a birefringent material for this element - crystalline quartz - it is necessary to keep the crystalline axis correctly oriented within the manufactured plate. For the correct crystalline lattice orientation we employ an X-Ray goniometer that assures the correct orientation within minutes of arc (see Figure 3 - Left). This operation is directly followed by referencing of the plate with flat surface on its circumference using standard CNC grinding technology (Figure 3 - Right).

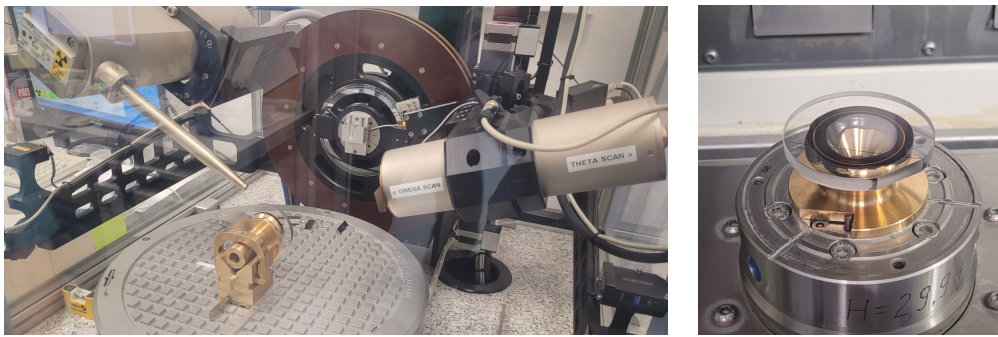


Figure 3: Left: Usage of the X-Ray goniometer for the crystal axis orientation within the plate. Right: Realization of a reference surface defining the position of the crystal axis within the plate.

3.2 Basic manufacturing

When all four plates are properly oriented, the standard optical production starts. It contains classical optical operations such as grinding and polishing. In addition to these standard processes, we have also applied wedging of the plates as they contain 0.12° and 0.18° . Figure 4 shows thickness measurement during the grinding of the wedge. It can be seen from the figure that the plates are processed in pairs so that the very same thickness and wedge is generated during the production.



Figure 4: Thickness measurement of one pair of plates during the grinding and wedging process.

3.3 Bonding and final correction polishing

The bonding procedure follows when all the plates are realized. The bonding is realized using NOA61 that has a vast space heritage for similar applications. The image showing the process of one-pair plate bonding can be seen in Figure 5. There are several things that need to be considered during the bonding procedure:

- The plates are glued together with the wedged surfaces so that the crystal axis stays perpendicular to the optical axis of the assembly.
- There is a relatively big separation of $30\text{ }\mu\text{m}$ between individual plates that helps the adhesive to overcome the coefficient of thermal expansion (CTE) difference in different crystal axis orientation of the individual plates.
- The air-gap is stabilized by temporal glass blocks on the plates circumference.

However, 4-plates bonded element with the air-gaps of $30\text{ }\mu\text{m}$ experienced surface form degradation so that further corrective re-polishing had to occur. Nevertheless, the process was relatively straightforward and iterated well towards the requirement of 1 fringe flatness over the optical aperture (see Figure 6).

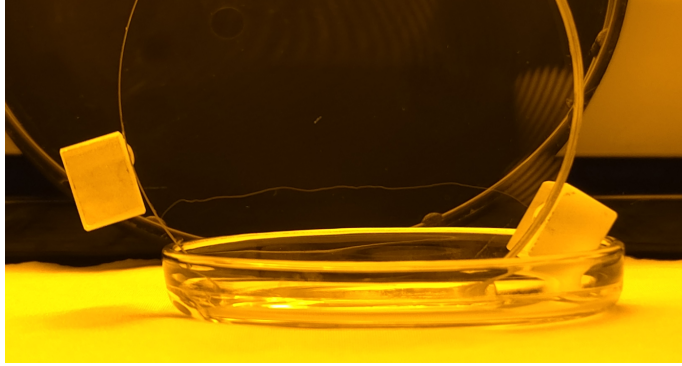


Figure 5: A pair of wedged plates during the bonding procedure. The curvy line shows the border of the adhesive that is sucked to the air-gap between the plates by capillary forces. The air-gap is $30\text{ }\mu\text{m}$ wide and stabilized by temporal blocks on the plates circumference.

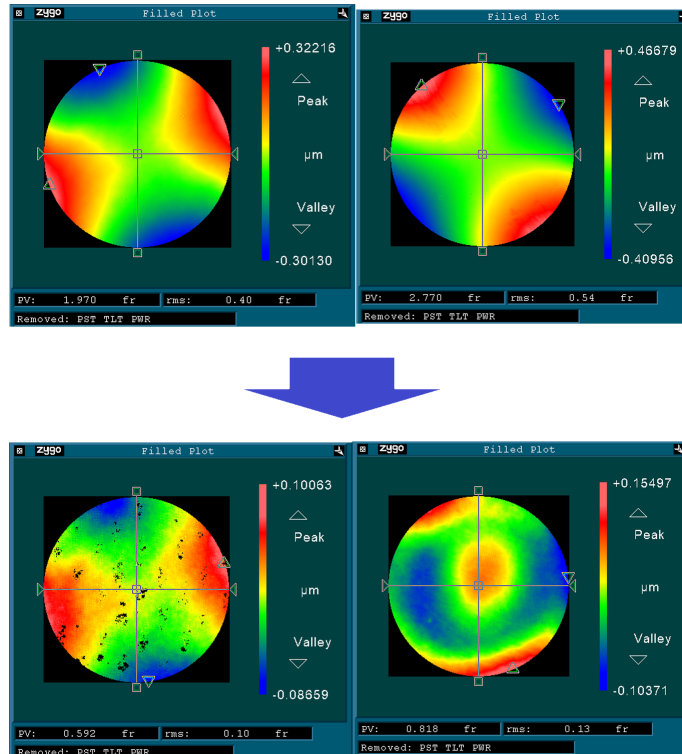


Figure 6: A degradation of the surface form after the bonding (top pair of images) that was corrected with final re-polishing step (bottom pair of images).

4 Characterization

To verify the functionality of the scrambler, a series of measurements was performed during and after manufacturing. The depolarization performance and the associated “diamond effect” were evaluated and compared with simulations carried out both in-house and by AIRBUS Defence and Space. All measurements were conducted using an experimental setup, in which the scrambler was positioned between two polarizers [7].

A monochromator was selected as the light source to provide any wavelength required for the measurement. The output of the source was coupled into an optical fiber and guided to the remainder of the setup. The main section consisted of a fiber ferrule emitting diverging light from the monochromator, which was then collimated by lens L1 ($f_{L1} = 180$ mm). The collimated beam subsequently propagated through the first polarizer, the polarization scrambler, and the second polarizer, before being focused by a lens L2 ($f_{L2} = 180$ mm) onto a camera detector. Both polarizers were mounted on motorized rotating stages. The camera used for most of the measurements was a Basler ace acA5472-17um.

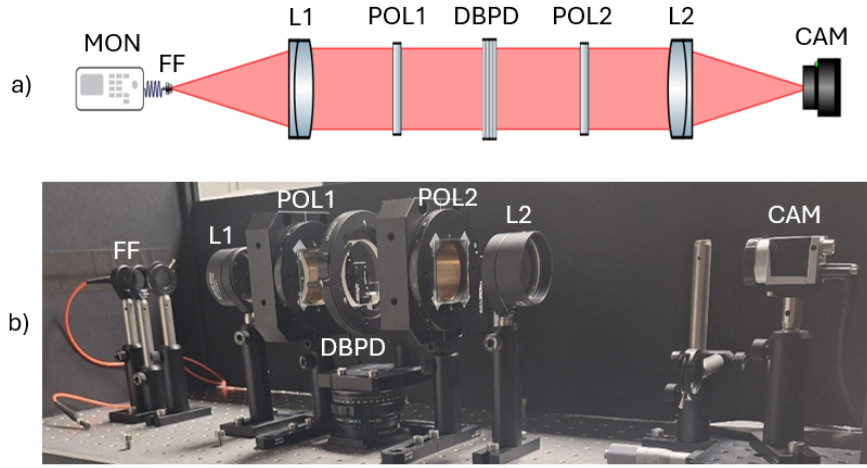


Figure 7: Experimental measurement setup. (a) Schematic representation of the experimental configuration and (b) photograph of the realized measurement setup: MON - monochromator; FF - fiber ferrule; L1 - collimating lens; POL1, POL2 - polarizers; DBPD - Dual Babinet Pseudo Depolarizer; L2 - focusing lens; CAM - camera.

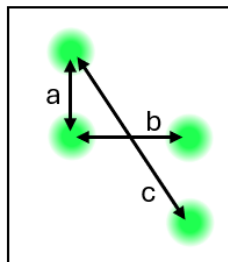
4.1 Spot separation

To quantify the image degradation caused by the depolarizer, commonly referred to as the diamond effect, a spot separation measurement was performed. The separation between the individual spots produced by the scrambler originates from the birefringence of the material and from the wedge geometries. Therefore, the spot separation measurement also provides an indirect verification of the manufactured wedge angles.

The distances between the spots were significantly smaller than the spot size itself, mainly due to the small wedge angles and the light source used in the setup (the end of a multi-mode fiber).

For this reason, a dedicated measurement procedure was developed to determine the spot positions accurately. The visibility of the individual spots on the camera can be controlled by rotating the polarizers to specific orientations. By carefully selecting these orientations, the individual spots were isolated such that only one of the four spots was visible on the camera at a time. The precise sub-pixel position of each spot was then obtained by calculating the centroid of the corresponding image. From these centroid positions, the spot separation distances were computed and compared with ZEMAX simulations.

The spot separation was measured at two wavelengths and for several different scrambler orientations. The results for 550 nm are shown in Fig. 8. With the exception of one value, all distances obtained from the measurements agree with the simulated values within one camera pixel ($2.4 \mu\text{m}$). This agreement confirms that the manufactured wedge angles are consistent with the design values. It also indicates that the observed spot separation, and therefore the diamond effect, remains within the expected range. The remaining discrepancy may be attributed to measurement uncertainty, residual alignment differences between the simulation and the experimental setup, or uncertainties in the centroid determination caused by the finite spot size.



	Distance	Sim	X0Y0	X5Y0	X-5Y0	X0Y5	X0Y-5	X5Y5
a		3.6	4.6	5.3	5.4	5.1	4.4	4.8
b		7.2	8.5	8.7	8.8	8.6	8.8	7.4
c		16.1	15.3	14.9	15.2	14.9	15.4	13.3

Figure 8: Spot separation results. Definition of the evaluated distances and their corresponding values for both simulation and measurement in different scrambler orientations. The orientations are defined by tilts about the x - and y -axes, with the z -axis corresponding to the optical axis. All distance values are given in μm .

4.2 Degree of polarization

To accurately evaluate the depolarization performance of the scrambler, both the method for determining the degree of polarization (DoP) and the measurement procedure were defined. Four orientations of the second polarizer (POL2), namely 0° , 45° , 90° , and 135° , were selected. For each wavelength and POL2 orientation, the measurement consisted of recording the intensity using a camera while rotating the first polarizer over a full 360° cycle. The degree of polarization was subsequently calculated from the maximum and minimum intensity values obtained for each wavelength and POL2 orientation.

$$DoP_{(wvl, POL2)} = 100 * \frac{I_{max(wvl, POL2)} - I_{min(wvl, POL2)}}{I_{max(wvl, POL2)} + I_{min(wvl, POL2)}} \quad (1)$$

The validation of the measurement method and the procedure was carried out by conducting a reference measurement without the scrambler. This was performed primarily to verify the correct operation of the polarizers and to ensure that the partially polarized light emitted by the

monochromator did not affect the measurement. In the ideal case, the intensity recorded by the camera would follow a perfect sinusoidal dependence with minima approaching zero. As shown in Fig. 9, the measured response is in close agreement with this ideal behavior, with the degree of polarization calculated from the measured intensity averaging around 99.9992%.

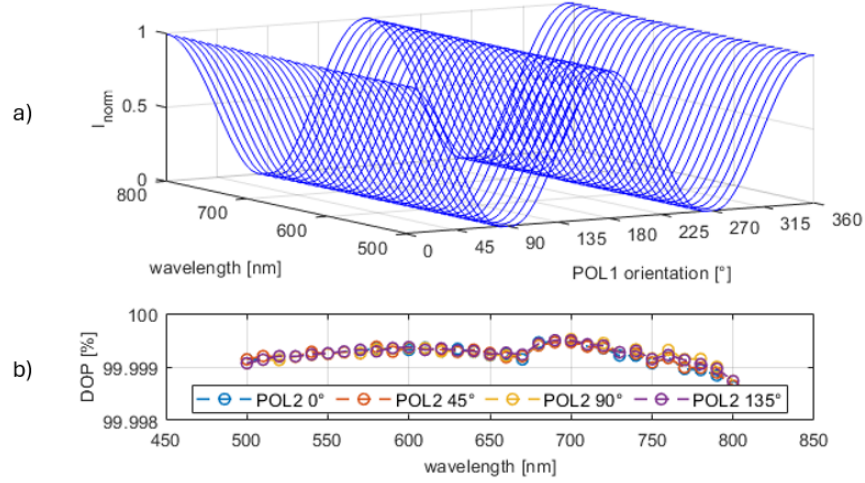


Figure 9: Validation results. (a) Normalized intensity values for POL2 at 0°. (b) Calculated values of DoP for four positions of POL2.

A series of measurements was performed during and after the final stages of manufacturing. The first two measurements were carried out after the bonding process and before correction polishing. The aim of these measurements was to assess the effect of thermal vacuum testing on the ability of the scrambler to depolarize light. One measurement was performed before and the other after TVAC testing, and the results were subsequently compared, as shown in Fig. 10. The comparison shows that the bakeout did not have any significant effect on the depolarization performance of the element, particularly at shorter wavelengths. The differences observed at longer wavelengths may also be attributed to a slightly different position of the scrambler in the measurement setup. This was later confirmed by both measurements and simulations, which showed that even small positioning uncertainties of the element during measurement can affect the results.

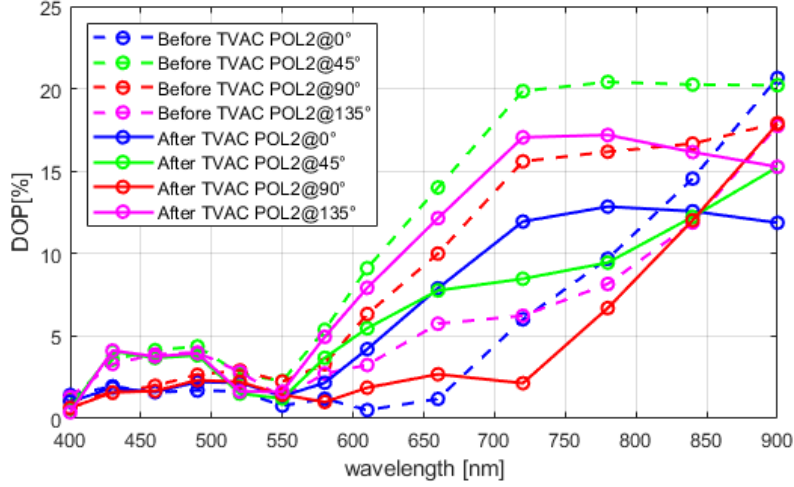


Figure 10: DoP results before and after thermal vacuum (TVAC) testing of the depolarizer.

At this stage, the scrambler surface form was significantly affected by astigmatism (see Figure 6); therefore, all subsequent measurements were carried out after correction polishing of the front and back surfaces of the scrambler. The measurement results, compared with ZEMAX simulations of an ideal scrambler, are shown in Fig. 11. For each measurement, the scrambler was removed from the setup and subsequently reinstalled. Therefore, slight differences in its position between individual measurements may have contributed to small variations in the measured results.

As shown by the results, the achieved DoP values reach a maximum of approximately 15% at longer wavelengths, demonstrating very good functionality of the scrambler. The measurements are also in good agreement with the ZEMAX simulation of an ideal scrambler. In most of the shorter-wavelength region, the measured values are almost identical to the simulated ones. Slight differences compared to the simulation, especially for POL2 at 0° and 90°, are most likely the result of the imperfect scrambler position in the measurement setup. At longer wavelengths, however, the measurement and simulation show slightly different trends, particularly due to the absence of the dip around 750 nm in the measured results compared with the simulation. This discrepancy was therefore investigated further.

First, a series of simulations was performed to identify possible causes of the discrepancy. Although variations in the scrambler position, including decentration, tip, and tilt, as well as variations in scrambler properties, such as wedge angle and crystal-axis orientation, affected the resulting DoP, none of these variations led to full agreement with the measured results. Second, control measurements were performed using several different recording devices to rule out the influence of the camera. A powermeter, two different VIS cameras, and a SWIR camera were used, while the position of the scrambler remained identical for all these measurements. The results show that all measurement devices provide similar results and that the same discrepancy with respect to the simulation remains. This indicates that the observed mismatch is not caused by the camera. To fully understand this discrepancy, additional simulations and measurements will be required.

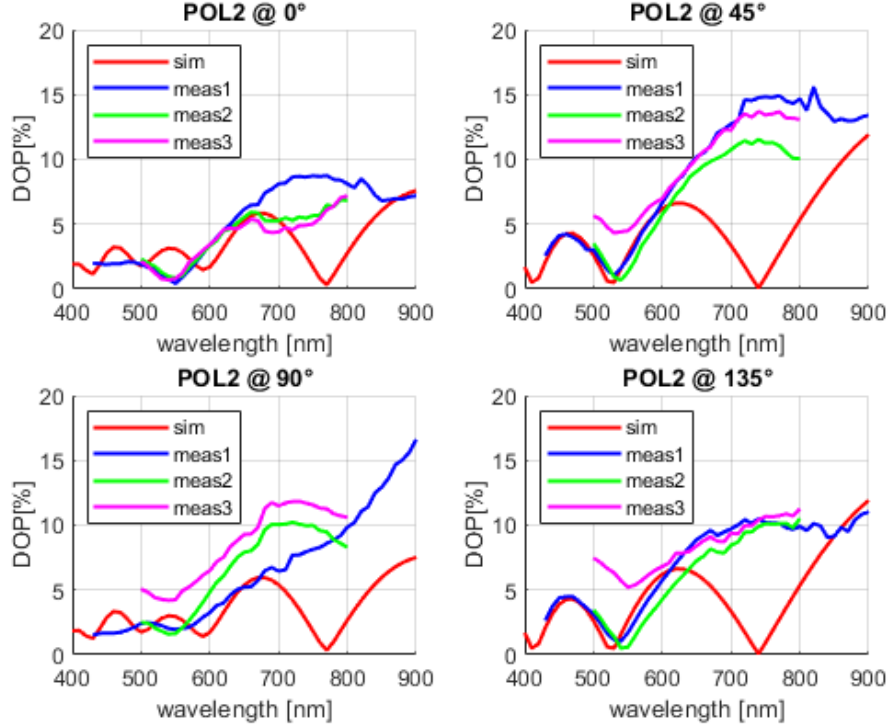


Figure 11: DoP measurement results when compared to ZEMAX simulation of ideal scrambler for each predefined POL2 orientation.

5 Conclusion

The design, manufacturing, and experimental characterization of a large-aperture Dual Babinet Pseudo Depolarizer for the TRUTHS HIS instrument were successfully completed. The manufacturing was carried out directly according to the developed production approach, including crystal-axis referencing, precision wedge fabrication, bonding, and final correction polishing. Despite the surface-form degradation observed after bonding, the corrective polishing process successfully restored the required optical quality, and the final element fulfilled the specified customer requirements.

The spot-separation measurements showed very good agreement with the ZEMAX simulations. With only a minor exception, the measured distances agreed with the simulated values within one camera pixel, confirming that the manufactured wedge angles are consistent with the design and that the resulting diamond effect remains within the expected range.

The measured degree of polarization further confirmed the high depolarization efficiency of the scrambler over a broad spectral range. At shorter wavelengths, the measured DoP closely follows the simulated response, with only small deviations that can most likely be attributed to uncertainties in the positioning of the scrambler in the measurement setup. The sensitivity of the measured DoP to

small changes in scrambler position was also observed experimentally and reproduced in simulations. At longer wavelengths, the measured response differs slightly from the ideal ZEMAX prediction, most notably by the absence of the simulated dip around 750 nm. A number of potential causes, including scrambler position, wedge-angle and crystal-axis variations, as well as the influence of the detector, have already been investigated; however, none has yet fully explained this discrepancy. Further simulations and measurements are therefore ongoing to clarify its origin.

Nevertheless, these remaining differences do not compromise the overall performance of the component. The scrambler achieves a substantial reduction of the degree of polarization across a wide spectral range, with measured DoP values remaining approximately below 15% even at the longer wavelengths investigated. Together with the successful manufacturing, compliance with the specified requirements, and close agreement between measured and simulated spot separation, these results demonstrate not only the effective broadband depolarization performance of the developed DBPD, but also our capability to design, manufacture, assemble, and characterize highly demanding birefringent optical components with the precision required for state-of-the-art space-borne hyperspectral instrumentation.

CRediT authorship contribution statement

Michal Jiránek: Writing – review & editing, Writing – original draft, Formal analysis, Methodology, Investigation, Validation, Conceptualization, Data Curation, Visualization. Radek Melich: Writing – review & editing, Writing – original draft, Formal analysis, Methodology, Investigation, Conceptualization, Funding acquisition. Pavel Psota: Writing – review & editing, Formal analysis, Methodology, Conceptualization. Munadi Ahmad: Data Curation, Formal analysis, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used an AI-based language assistance tool (ChatGPT) to support English language refinement, stylistic clarity, and editorial consistency of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the scientific content, interpretations, and conclusions of the published article.

References

- [1] Nigel Fox and Paul Green. “Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS): An element of a space-based climate and calibration observatory”. en. In: *Remote Sens. (Basel)* 12.15 (July 2020), p. 2400.
- [2] Bena Mero et al. “Status of the design, accommodation and performance of the TRUTHS Hyperspectral Imager at the end of phase B1”. In: *International Conference on Space Optics — ICSO 2022*. Ed. by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny. Dubrovnik, Croatia: SPIE, July 2023.
- [3] James P McGuire Jr and Russell A Chipman. “Analysis of spatial pseudodepolarizers in imaging systems”. In: *Polarization Considerations for Optical Systems II*. Ed. by Russell A Chipman. San Diego: SPIE, Jan. 1990.
- [4] G Lichtenberg et al. “SCIAMACHY Level 1 data: calibration concept and in-flight calibration”. en. In: *Atmos. Chem. Phys.* 6.12 (Nov. 2006), pp. 5347–5367.
- [5] Jean-Loup Bézy et al. “Polarization scramblers in Earth observing spectrometers: lessons learned from Sentinel-4 and 5 phases A/B1”. In: *International Conference on Space Optics — ICSO 2012*. Ed. by Errico Armandillo, Nikos Karafolas, and Bruno Cugny. Ajaccio, Corsica, France: SPIE, Nov. 2017.
- [6] X Liu et al. “Stitching type large aperture depolarizer for gas monitoring imaging spectrometer”. en. In: *ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* XLII-3 (Apr. 2018), pp. 1141–1144.
- [7] G Dubroca et al. “Sodern recent development in the design and verification of passive polarization scramblers for space applications”. In: *International Conference on Space Optics — ICSO 2016*. Ed. by Nikos Karafolas, Bruno Cugny, and Zoran Sodnik. Biarritz, France: SPIE, Sept. 2017.