

Analysis of the polarization behavior of scramblers included in instrumentation for Earth Observation missions

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ABSTRACT

The study of air quality, ozone layer depletion and greenhouse gases are challenges for our society today. These gases absorb solar radiation in different regions of the electromagnetic spectrum, with absorption spectroscopy being the reference technique used to monitor them in Earth Observation missions. However, to ensure maximum precision in radiometric measurements, onboard optical instrumentation must be insensitive to incident light polarization. Therefore, instruments incorporate scramblers, consisting of two birefringent prisms with opposite angles that introduce different phase retardations to depolarize light. Designing and integrating these components requires a preliminary study that relates the optical design parameters of the scrambler with the polarization sensitivity. Additionally, an analysis of the scrambler's influence is needed on the instrument's performance.

In the space environment, these elements are exposed to hostile space environmental conditions, which can cause degradation of optical properties, resulting in a reorientation of the crystal's main optical axes. In birefringent components, phase retardation depends on the material's birefringence and crystal axis orientation. Consequently, variations due to space environmental conditions can result in unexpected phase shifts, compromising the expected depolarization performance. Therefore, it is necessary a detailed characterization of the depolarizer.

This work presents the optical set-up developed for the optical and polarization characterization of crystalline quartz scramblers used for space spectrometers. The methodology focuses on evaluating the depolarization capability by measuring the degree of polarization. The formalism used is based on Mueller matrices and Stokes vectors. This configuration aims to evaluate the depolarization capability of these crystals allowing them to be comprehensively characterized to quantify the variations of the polarization degree.

Keywords: Spectroscopy, atmospheric observation, polarization, scramblers, CubeSat, Stokes vector.

1. INTRODUCTION

Earth Observation missions dedicated to monitoring atmospheric compounds and greenhouse gases are frequently based on absorption spectroscopy. To achieve the requisite of precise radiometric measurements and high Signal-to-Noise Ratio (SNR), onboard optical instruments must mitigate the effects of incident light polarization. This polarization is primarily introduced by atmospheric Rayleigh scattering, particularly at shorter wavelengths. This is due to the fact that this scattering has an inverse dependence on the fourth power of the wavelength, i.e., it is proportional to $1/\lambda^4$ [1].

In the specific absorption bands used to monitor these atmospheric gases, the atmosphere becomes highly opaque and Rayleigh scattering dominates, leading to a high Degree of Polarization (DOP) that can make the minimum detectable radiance signals difficult to detect [2]. As established in our previous work [3], instruments must be capable of detecting minimum radiance differences above noise, forcing to reduce measurement errors caused by the polarization of the incoming light. In such precision instruments and missions, the polarization sensitivity is typically below 5% [4, 5]. For that reason, the instruments used in absorption spectroscopy must incorporate depolarizers or scramblers that allow detecting minimum radiance differences without any loss of flux.

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1.1 Scrambler definition

A scrambler is an optical element designed to modify the DOP of incident light by significantly reducing or eliminating it. These optical components typically consist of one or more prisms fabricated from birefringent materials, such as crystalline quartz. The prisms are located with opposing wedge angles (α), ensuring that the entrance and exit surfaces remain parallel while creating a thickness (t) variation across the clear aperture that is opposite between the two wedges. Depending on the type of the scrambler, such as Lyot [6] or Horizontal-Vertical (HV) [7] configurations, the orientation of the principal crystal axis for each birefringent prism, as well as the specific wedge thickness, will vary accordingly (Figure 1).

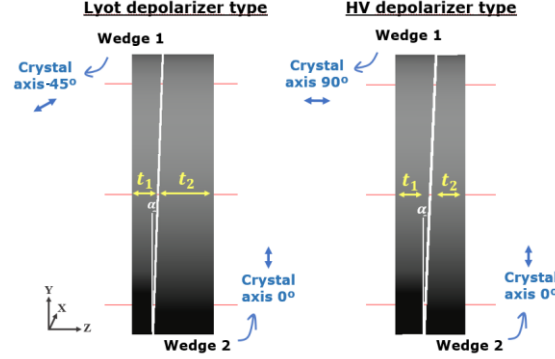


Figure 1. Optical layout of a Lyot (left) and a HV (right) scrambler.

The depolarization capability of the scramblers relies on the birefringent material, that decomposes the incident polarized light into two orthogonal principal axes (the ordinary and extraordinary components) by introducing a phase shift ($\Delta\phi$) to each component. The phase difference introduced by the scrambler for a point in its aperture (h) depends on the scramblers' design parameters, including prism thickness, operating wavelength, refractive index and prism angle, and can be expressed as follows in (1),

$$\Delta\phi(h) = \frac{2\pi}{\lambda} \cdot \Delta n \cdot (t_1(h) - t_2(h)) = 2\pi q \quad (1)$$

where h represents the aperture point along the Y-axis, λ is the wavelength, Δn the quartz refractive index difference, t_1 the thickness of the first prism at height h , t_2 the thickness of the second prism at the same height h , and q the number of cycles of retardation variation [8].

Due to the fact that the phase shift depends on the spatial coordinates, the retardation varies continuously across the scrambler aperture. This variance generates a pseudo-random distribution of polarization states along its aperture (X, Y), independently of the polarization state of the incident light. Each polarization state in the aperture can be defined by its corresponding Stokes vector [9]. When the beam of light fills a sufficiently large instrument pupil, these polarization states are spatially averaged. When the scrambler depolarizes completely, the average of the Stokes vectors along the scrambler aperture converts the incoming light into a pseudo-random unpolarized beam before it reaches the detector, where only the vector element S_0 , related to the intensity, has a non-zero normalized value ($0 < S_0 < 1$).

1.2 Implications of introducing scramblers in a spectrometer

Integrating these components into an optical instrument, specifically spectrometers for Earth Observation missions, introduces critical design compromises. As evaluated in our previous analysis [3], the depolarization efficiency is dependent on the spectrometer's design parameters, such as the instrument's pupil size, the operating wavelength and the Field of View (FoV). For instance, a larger pupil aperture allows a more efficient spatial averaging of the polarization states (reducing the DOP), whereas an increase in the operating wavelength generally decreases the depolarization efficiency. Furthermore, for instruments with larger FoVs, the decentering of off-axis rays at the scrambler plane generates non-uniformities in the DOP across the aperture.

On the other hand, due to the fact that the scramblers are birefringent, they impact the instrument's overall optical performance. Scramblers decompose the incident light into ordinary and extraordinary rays, that propagate in slightly

different directions, which generates multiple Point Spread Functions (PSFs) and produces image doubling in the image plane. A compromise therefore exists between achieving optimal depolarization efficiency and maintaining optical quality: increasing the phase retardation (e.g., with larger wedge angles or thickness variations) improves depolarization, but increases the spatial separation between the PSFs, thereby distributing the energy over a larger area and degrading image quality.

The image doubling affects the spatial and spectral resolution of the spectrometer. Since each PSF generates an independent image of the spectrometer entrance (slit in this case), multiple PSFs can lead to an overlap of adjacent wavelengths, deteriorating the spectral resolution. To prevent this image doubling from compromising the spectral measurements, a precise alignment must be implemented. Specifically, rotating the scrambler by 90° around its optical axis can shift the image overlap from the spectral direction to the spatial direction [3]. Although this rotation introduces an inhomogeneous intensity distribution spatially, it allows to maintain the spectral resolution.

To completely validate these theoretical models and analyze the scramblers' behavior under real operating conditions, a rigorous optical characterization of the scrambler's depolarization is necessary. To this end, this work presents the optical set-up developed for the laboratory characterization of scramblers, as well as the subsequent simulations that allow us to verify these experimental results.

2. METHODOLOGY

2.1 Set-up for Depolarization Degree measurement

The set-up used to measure the DOP at the output of the scramblers (Figure 2) consists of a laser operating at 670nm, a diaphragm (Stop) to define the diameter of the entrance beam of light (21mm), a Polarization State Generator (PSG) composed of a polarizer (POL1) and a quarter-wave plate (QWP1), and a Polarization State Analyzer (PSA) composed of a second polarizer (POL2) and a second quarter-wave plate (QWP2). Finally, a collector lens has been placed before the power-meter. Since depolarization depends on the scrambler's aperture (21mm), it is necessary to capture all the light passing through it. Given that the sensor area of the power-meter is smaller (10mm^2), the collector lens allows to collect the entire beam of light. Scramblers are later located between the PSG and PSA. The DOP is determined through the intensity measurements which are performed inside a clean-room ISO7.

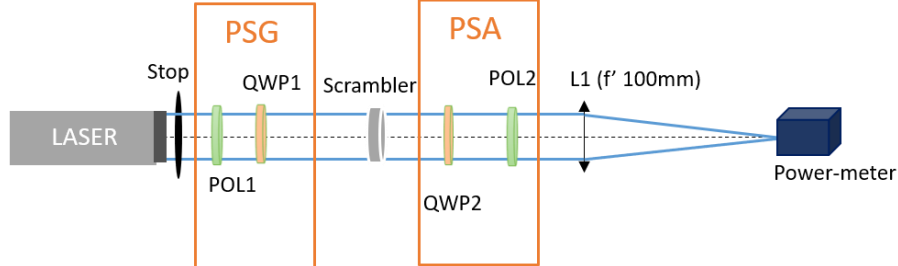


Figure 2. Schematic of the experimental set-up.

Prior to evaluating the scramblers, a characterization of the laser stability and optical elements is required. The transmittances of the polarizers and quarter-wave plates at 670nm were measured. Specifically, the transmittances for the first and second polarizers (POL1, POL2) had a value of 71% and 74%, respectively, while the first and second quarter-wave plates (QWP1, QWP2) had transmittances of 96% and 94%.

In addition, the stability of the laser in terms of polarization and intensity has been evaluated, showing that a 40 minutes stabilization time is needed. After that, the laser variations are approximately 2nW, which are comparable to the background dark noise.

Next, the polarization state of the laser has been determined (S_{laser}). For this purpose, the PSA is located after the laser and it is adjusted to measure the intensities corresponding to six different polarization states in the laser output (I_{corr}): Horizontal (I_H), Vertical (I_V), $+45^\circ$ (I_{+45}), -45° (I_{-45}), Right Circular (I_{RC}) and Left Circular (I_{LC}). The Stokes vector of the laser (S_{laser}) has been obtained by multiplying the measured intensity vector (I_{corr}) by the pseudo-inverse of the analyzer matrix (A^+),

$$\mathbf{S}_{laser} = \mathbf{A}^+ \cdot \mathbf{I}_{corr} \quad (2)$$

where $\mathbf{I}_{corr}$ is the intensity vector defined as $\mathbf{I}_{corr} = (I_H, I_V, I_{+45}, I_{-45}, I_{RC}, I_{LC})^T$, and $\mathbf{A}$ is the analyzer (PSA) matrix defined as shown in (3). This matrix accounts for the measured transmittances of the second polarizer ($T_{POL2} = 0.74$) and the second quarter-wave plate ($T_{QWP2} = 0.94$):

$$\mathbf{A} = \frac{1}{2} \cdot T_{POL2} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 \\ T_{QWP2} & 0 & 0 & T_{QWP2} \\ T_{QWP2} & 0 & 0 & -T_{QWP2} \end{pmatrix} \quad (3)$$

By solving (2) with the experimental values of intensity (4), the normalized Stokes vector of the laser ($\mathbf{S}_{laser,norm}$) obtained are presented in (5).

$$\mathbf{I}_{corr} = \begin{pmatrix} I_H \\ I_V \\ I_{+45^\circ} \\ I_{-45^\circ} \\ I_{RC} \\ I_{LC} \end{pmatrix} = \begin{pmatrix} 159.803 \\ 12.667 \\ 0.481 \\ 161.515 \\ 159.811 \\ 162.452 \end{pmatrix} \quad (4)$$

$$\mathbf{S}_{laser,norm} = \begin{pmatrix} 1.000 \\ -0.079 \\ -0.003 \\ -1.006 \end{pmatrix} \quad (5)$$

2.2 Polarimetric measurements and DOP calculation

To determine the DOP at the output of the scramblers and evaluate their polarization properties, a methodology has been established following the Mueller matrix formalism presented in our previous work [3]. As explained above, the complete experimental set-up consists of three main blocks (Figure 2): a Polarization States Generator (PSG) combined with a stabilized laser source, the optical sample under test (the scrambler), and a Polarization States Analyzer (PSA), finally aligned with a collector lens (L1) and a power-meter.

The evaluation of the DOP requires determining the spatially averaged Stokes vector at the output of the scramblers, from which the DOP can be subsequently calculated. However, the power-meter of the set-up can register only the intensity of the light and the polarization state at the output of the scramblers cannot be measured directly. Consequently, this Stokes vector must be calculated from the intensity measurements with Mueller matrices.

By multiplying Mueller matrices of each optical element of the set up in the reverse direction of light propagation, the sequence of polarization states along the set-up can be calculated. This implies to calibrate the whole optical system prior to measuring the scramblers. This calibration requires characterizing the generation matrix of the PSG ($\mathbf{W}$) and the modulation matrix of the PSA ($\mathbf{O}$). Once the modulation matrix ($\mathbf{O}$) is known, it acts as the operator relating the output intensities to the corresponding Stokes vectors entering the analyzer. Next, the derivation of these matrices is detailed.

The generation matrix ($\mathbf{W}$) of the system is formed by the laser and PSG and defines the six polarization states exiting the PSG before reaching the analyzer. This matrix is derived from the theoretical Mueller matrices of the optical elements that constitute the PSG [9] for the six polarization configurations: Horizontal, Vertical, $+45^\circ$, -45° , Right Circular and Left Circular, which are calculated theoretically by orienting the first polarizer (POL1) and the first quarter-wave plate (QWP1). For the generation of the linear polarization states, the configurations are defined by the generalized Mueller matrix (6) of a linear polarizer rotated by an angle $\theta=0^\circ, 90^\circ, +45^\circ$ and -45° , considering its experimental transmittance (T_{POL1}):

$$\mathbf{M}_{POL}(\theta) = \frac{T_{POL1}}{2} \begin{pmatrix} 1 & \cos(2\theta) & \sin(2\theta) & 0 \\ \cos(2\theta) & \cos^2(2\theta) & \sin(2\theta)\cos(2\theta) & 0 \\ \sin(2\theta) & \sin(2\theta)\cos(2\theta) & \sin^2(2\theta) & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (6)$$

For the generation of the circular polarization states (RC and LC), the quarter-wave plate is oriented at $+45^\circ$. This optical element is represented by its specific Mueller matrix for this angle (7), taking into account its respective transmittance (T_{QWP1}):

$$\mathbf{M}_{QWP1} = T_{QWP1} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \quad (7)$$

To define the final configurations for the circular polarization states of the PSG, this quarter-wave plate matrix is multiplied by the linear polarizer matrix $\mathbf{M}_{POL}(\theta)$. Specifically, the RC state is generated by multiplying the $\mathbf{M}_{QWP1}$ matrix defined in (7) by the linear polarizer matrix $\mathbf{M}_{POL}(90^\circ)$ (6), while the LC state is obtained in a similar manner by multiplying $\mathbf{M}_{QWP1}$ by $\mathbf{M}_{POL}(0^\circ)$.

Next, the resulting Mueller matrix of each of the six configurations of the PSG is multiplied by the previously determined Stokes vector of the laser ($\mathbf{S}_{laser}$). By grouping the resulting six column vectors, the complete generation matrix ($\mathbf{W}$) is constructed (8). Each column of $\mathbf{W}$ matrix corresponds to each of the six polarization configurations (H, V, $+45^\circ$, -45° , RC, LC) and each row of $\mathbf{W}$ corresponds to the Stokes parameters (S_0, S_1, S_2, S_3).

$$\mathbf{W} = \begin{pmatrix} \mathbf{H} & \mathbf{V} & +45 & -45 & \mathbf{RC} & \mathbf{LC} \\ 52.1498 & 61.0793 & 56.4450 & 56.7840 & 58.3375 & 49.8089 \\ 52.1498 & -61.0793 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 56.4450 & -56.7840 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 58.3375 & -49.8089 \end{pmatrix} \begin{matrix} \mathbf{S}_0 \\ \mathbf{S}_1 \\ \mathbf{S}_2 \\ \mathbf{S}_3 \end{matrix} \quad (8)$$

Once $\mathbf{W}$ is calculated, the next step is to determine the experimental modulation matrix $\mathbf{O}$ of the analyzer. To calculate this matrix, it is first necessary to configure the measurement set-up to acquire the experimental intensity matrix ($\mathbf{I}$). This is achieved by coupling the six incident polarization states produced by the PSG (H, V, $+45^\circ$, -45° , RC, LC) with the six polarization states of the PSA. Specifically, for each of the six generated PSG states, the PSA was sequentially configured to measure four linear states (by orienting POL2 at 0° , 90° , $+45^\circ$, and -45°) and two circular states (by introducing QWP2 at $+45^\circ$ followed by POL2 at 0° for RC, and at $+90^\circ$ for LC). This combination generates a total of 36 measurements. In the resulting matrix $\mathbf{I}$, the rows correspond to the six incident states generated by the PSG, while the columns represent the intensities measured under each of the six PSA configurations. The final corrected experimental intensity matrix, expressed in μW , is given by (9):

$$\mathbf{I} = \begin{pmatrix} \mathbf{H} & \mathbf{V} & +45 & -45 & \mathbf{RC} & \mathbf{LC} \\ 40.215 & 0.015 & 19.078 & 20.810 & 20.895 & 16.802 \\ 0.001 & 47.167 & 24.352 & 22.956 & 20.235 & 24.898 \\ 22.016 & 20.930 & 43.460 & 0.007 & 20.993 & 20.066 \\ 21.331 & 22.486 & 0.016 & 43.900 & 20.754 & 21.313 \\ 20.194 & 24.435 & 23.447 & 21.258 & 42.689 & 0.474 \\ 21.006 & 17.074 & 17.965 & 20.114 & 0.451 & 35.920 \end{pmatrix} \begin{matrix} \mathbf{H} \\ \mathbf{V} \\ +45 \\ -45 \\ \mathbf{RC} \\ \mathbf{LC} \end{matrix} \quad (9)$$

With both matrices $\mathbf{W}$ and $\mathbf{I}$ defined, the experimental modulation matrix of the analyzer ($\mathbf{O}$) can now be constructed. Since $\mathbf{I}$ contains the measured output intensities and $\mathbf{W}$ defines the generated input states, the value of the modulation matrix $\mathbf{O}$ is directly determined by multiplying the intensity matrix ($\mathbf{I}$) by the pseudo-inverse of the generation matrix ($\mathbf{W}^+$), as follows (10),

$$\mathbf{O} = \mathbf{I} \cdot \mathbf{W}^+ \quad (10)$$

yielding the following experimental modulation matrix of the analyzer (11):

$$\mathbf{O} = \begin{pmatrix} \mathbf{S}_0 & \mathbf{S}_1 & \mathbf{S}_2 & \mathbf{S}_3 \\ 0.3841 & 0.3853 & 0.0072 & -0.0378 \\ 0.3836 & -0.3864 & -0.0126 & 0.0376 \\ 0.3830 & -0.0163 & 0.3848 & 0.0204 \\ 0.3861 & 0.0114 & -0.3865 & -0.0200 \\ 0.3683 & 0.0351 & 0.0032 & 0.3617 \\ 0.3650 & -0.0427 & -0.0099 & -0.3566 \end{pmatrix} \begin{matrix} \mathbf{H} \\ \mathbf{V} \\ +45 \\ -45 \\ \mathbf{RC} \\ \mathbf{LC} \end{matrix} \quad (11)$$

Once $\mathbf{O}$ is known, the scrambler can be characterized, determining its Stokes vector and DOP of the light at the output of it following the relation $\mathbf{I}_{meas} = \mathbf{O} \cdot \mathbf{S}_{in}$, where $\mathbf{I}_{meas}$ is the intensity measured at the power-meter after passing the scrambler and after configuring the PSA into six different polarization states:

- Linear states: A second linear polarizer (POL2) is oriented at 0° (H), 90° (V), $+45^\circ$, and -45° .
- Circular states (RC and LC): A second quarter-wave plate (QWP2) is introduced with its fast axis fixed at $+45^\circ$, followed by POL2 oriented at 0° and $+90^\circ$, respectively.

This measurement sequence is systematically repeated for four incident polarization states generated by the PSG (H, V, $+45^\circ$, -45°) and the defined angular orientations of the scrambler itself (H, V, $+45^\circ$, -45°). By multiplying each measured intensity vector by the pseudo-inverse of the modulation matrix ($\mathbf{O}^+$), the Stokes vector ($\mathbf{S}_{in}$) entering the analyzer, which also corresponds to the Stokes vector at the output of the scrambler, is obtained (12),

$$\mathbf{S}_{in} = \mathbf{O}^+ \cdot \mathbf{I}_{meas} \quad (12)$$

where $\mathbf{S}_{in} = [S_0, S_1, S_2, S_3]^T$. From these Stokes parameters ($\mathbf{S}_{in}$), the resultant **DOP** of the light after passing through the scrambler is calculated using the standard equation (13) [9]:

$$\mathbf{DOP} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \quad (13)$$

The verification of the experimental results, DOP and Stoke vector, is performed through simulations using Code V optical design software.

3. RESULTS

This section presents the characterization of a commercial crystalline quartz Lyot scrambler and the results of comparing with Code V optical simulations. For those simulations, the polarization ray tracing was performed using an array of 51 rays across the aperture, 21mm, which is sufficient to compute the theoretical spatial average of the Stokes vectors and the expected DOP for multiple scrambler positions and incoming polarization states.

The commercial scrambler measured has a nominal wedge angle of 2 degrees and wedge thicknesses of $t_1 = 2.25mm$ and $t_2 = 4.95mm$. The experimental polarimetric evaluation was performed by applying the previously described methodology, determining the spatially averaged Stokes vectors and the DOP at the output of the scrambler for different incident polarization states and scrambler orientations.

Table 1 summarizes the scrambler Stokes vectors and degrees of polarization obtained through the Code V simulation versus the experimental results. The first column indicates the four scrambler orientations: POS1 (wedge 1 at $+45^\circ$ and wedge 2 at $+0^\circ$ (vertical axis)), POS2 (wedge 1 at $+135^\circ$ and wedge 2 at $+90^\circ$), POS3 (wedge 1 at $+180^\circ$ and wedge 2 at $+135^\circ$), and POS4 (wedge 1 at $+90^\circ$ and wedge 2 at $+45^\circ$) while the second shows the linear input polarization state, horizontal (H), vertical (V) or $\pm 45^\circ$. The Stokes vector parameters are normalized to S_0 .

Table 1. Results obtained for the DOP and normalized Stokes vectors from nominal Code V simulations and laboratory measurements for the commercial scrambler.

Scrambler orientation (°)	Input linear polarization state	Nominal Stokes Vector (S_0, S_1, S_2, S_3) (Code V)	DOP (%) (Code V)	Stokes vector (S_0, S_1, S_2, S_3) (Experimental)	DOP (Experimental) (%)
POS1	H	(1.000, 0.004, -0.473, -0.161)	50.0	(1.000, -0.016, -0.381, -0.055)	38.5 ± 1.1
	V	(1.000, -0.003, 0.470, 0.161)	50.0	(1.000, 0.013, 0.390, 0.048)	39.3 ± 1.0
	+45°	(1.000, -0.001, 0.007, -0.008)	1.0	(1.000, -0.073, -0.009, -0.009)	7.5 ± 0.6
	-45°	(1.000, 0.001, -0.007, 0.008)	1.0	(1.000, 0.072, 0.019, -0.001)	7.4 ± 0.6
POS2	H	(1.000, 0.004, -0.473, 0.161)	50.0	(1.000, -0.011, -0.389, 0.032)	39.0 ± 1.1
	V	(1.000, -0.003, 0.470, -0.161)	50.0	(1.000, 0.011, 0.399, -0.028)	39.8 ± 1.0
	+45°	(1.000, -0.001, 0.007, 0.008)	1.0	(1.000, -0.074, -0.004, -0.002)	7.4 ± 0.6
	-45°	(1.000, 0.001, -0.007, -0.008)	1.0	(1.000, 0.070, 0.012, -0.005)	7.2 ± 0.6
POS3	H	(1.000, 0.005, 0.001, 0.006)	0.7	(1.000, -0.005, 0.077, -0.005)	7.7 ± 1.0
	V	(1.000, -0.004, -0.001, -0.005)	0.7	(1.000, -0.001, -0.068, -0.005)	6.8 ± 1.0
	+45°	(1.000, 0.472, 0.002, -0.160)	49.8	(1.000, 0.388, -0.015, -0.017)	38.9 ± 0.6
	-45°	(1.000, -0.472, -0.002, 0.159)	49.8	(1.000, -0.391, 0.022, 0.006)	39.2 ± 0.7
POS4	H	(1.000, 0.005, 0.001, -0.006)	0.7	(1.000, -0.012, 0.075, -0.006)	7.6 ± 1.0
	V	(1.000, -0.004, -0.001, 0.005)	0.7	(1.000, 0.009, -0.068, -0.002)	6.9 ± 1.0
	+45°	(1.000, 0.472, 0.002, 0.160)	49.8	(1.000, 0.389, -0.007, -0.004)	38.9 ± 0.6
	-45°	(1.000, -0.472, -0.002, -0.159)	49.8	(1.000, -0.390, 0.017, 0.001)	39.0 ± 0.6

Analyzing the results, firstly it is observed that there is a difference larger than the uncertainty in the depolarization degree value between the nominal and the experimental data. The simulations predict a maximum DOP of approximately 50% and a minimum value of 1%, while the measurements yield values between 38-40% for the maximum and 7-8% for the minimum. On the other hand, it is observed that the distribution of the coefficients of the Stokes vectors varies in both sign and magnitude.

The high discrepancies of DOP between simulations and measurements are only explained with a relative rotation between the two wedges of the scrambler (γ) which is not specified by the scrambler manufacturer. However, the coefficients of Stokes discrepancies are not exclusively explained with this rotation between wedges, it is necessary to add the variation of scrambler thickness, considering this thickness inside the tolerance ranges given by the manufacturer.

In order to determine the values of the two factors that cause the discrepancies between simulation and measurements, an optical sensitivity analysis has been performed in Code V focusing on relative rotation between the two wedges of the scrambler (γ) and wedges thickness variation (t_1, t_2). This study shows that:

- A slight angular alignment error, i.e. a rotation γ between the two quartz wedges, varies the relative orientation of the main axes of both wedges having a direct impact on the spatial depolarization capability of the scrambler. A relative gamma rotation (γ) of less than 2 degrees between the wedges causes the maximum DOP to drop by 10% and the minimum DOP to increase by 7-8%, matching the experimental results.
- A wedge thickness variation inside tolerance barely affects the final DOP but acts as a retarder that introduces a variable phase shift (1), that rotates the polarization state at the output, significantly modifying the magnitude and sign of the output Stokes vectors. Modifying either the thickness of the first wedge (t_1) or the second wedge (t_2) individually produces the same behavior because the output polarization distribution depends on the optical path difference and therefore, the resulting phase retardation ($\Delta\phi$). Accordingly, even if two different manufactured

scramblers yield similar DOP values in a given configuration, their output polarization states will differ due to their specific manufacturing thickness deviations. For instance, depending on the exact phase retardation introduced, the output polarization Stokes in one scrambler might be concentrated entirely in the circular parameter (s_3), leaving the linear parameters (such as s_2) near zero. Conversely, in another scrambler with the exact same configuration, the thickness combination could maximize the phase shift toward a linear parameter, minimizing the circular one. In addition to these magnitudes' redistributions, the continuous phase variations also alter the signs of the Stokes parameters due to the periodic sinusoidal behavior of phase retardation.

Furthermore, these magnitude redistributions and sign changes in S_1 , S_2 and S_3 driven by thickness variations are independent of the relative rotation angle (γ) between the wedges, as this rotation only alters the DOP.

Therefore, following the sensitivity analysis, an optimization of Code V simulation was performed trying to replicate the experimental Stokes vectors and DOP values obtained in the laboratory validating them and the proposed methodology for scrambler polarimetric characterization. The optimization first determines the relative orientation angle between the two scrambler wedges that reproduces the DOP observed experimentally. Subsequently, a study is performed to analyze the evolution of the Stokes vectors as a function of the thickness variations in both wedges. The optimization results in an angle between the two wedges around 2° with $\gamma_1 = +1.36^\circ$ for the first wedge and $\gamma_2 = -0.73^\circ$ for the second one, and the simulated results matched the experimental data when setting the thicknesses to $t_1 = 2.434mm$ and $t_2 = 4.768mm$.

Table 2 presents a comparison between the measurements and the optimized Code V model incorporating the discrepancies of wedges rotation angle (γ) and the thickness of each wedge (t_1, t_2).

Table 2. Comparison between Code V optimized and experimental results for the measured scrambler.

Scrambler orientation ($^\circ$)	Input linear polarization state	Stokes vector (Code V) (s_0, s_1, s_2, s_3)	DOP (Code V) (%)	Stokes vector (experimental) (s_0, s_1, s_2, s_3)	DOP (Experimental) (%)
POS1	H	(1.000, -0.001, -0.382, -0.089)	39.3	(1.000, -0.016, -0.381, -0.055)	38.5 ± 1.1
	V	(1.000, 0.009, 0.388, 0.057)	39.3	(1.000, 0.013, 0.390, 0.048)	39.3 ± 1.0
	+45°	(1.000, -0.074, -0.020, 0.005)	7.7	(1.000, -0.073, -0.009, -0.009)	7.5 ± 0.6
	-45°	(1.000, 0.074, 0.020, -0.007)	7.7	(1.000, 0.072, 0.019, -0.001)	7.4 ± 0.6
POS2	H	(1.000, -0.009, -0.388, 0.057)	39.3	(1.000, -0.011, -0.389, 0.032)	39.0 ± 1.1
	V	(1.000, 0.009, 0.388, -0.057)	39.3	(1.000, 0.011, 0.399, -0.028)	39.8 ± 1.0
	+45°	(1.000, -0.074, -0.020, -0.007)	7.7	(1.000, -0.074, -0.004, -0.002)	7.4 ± 0.6
	-45°	(1.000, 0.074, 0.020, 0.007)	7.7	(1.000, 0.070, 0.012, -0.005)	7.2 ± 0.6
POS3	H	(1.000, -0.019, 0.074, -0.004)	7.7	(1.000, -0.005, 0.077, -0.005)	7.7 ± 1.0
	V	(1.000, 0.019, -0.074, 0.004)	7.7	(1.000, -0.001, -0.068, -0.005)	6.8 ± 1.0
	+45°	(1.000, 0.386, -0.008, -0.055)	39.0	(1.000, 0.388, -0.015, -0.017)	38.9 ± 0.6
	-45°	(1.000, -0.386, 0.008, 0.055)	39.0	(1.000, -0.391, 0.022, 0.006)	39.2 ± 0.7
POS4	H	(1.000, -0.019, 0.074, 0.004)	7.7	(1.000, -0.012, 0.075, -0.006)	7.6 ± 1.0
	V	(1.000, 0.019, -0.074, -0.004)	7.7	(1.000, 0.009, -0.068, -0.002)	6.9 ± 1.0
	+45°	(1.000, 0.386, -0.008, 0.055)	39.0	(1.000, 0.389, -0.007, -0.004)	38.9 ± 0.6
	-45°	(1.000, -0.386, 0.008, -0.055)	39.0	(1.000, -0.390, 0.017, 0.001)	39.0 ± 0.6

The DOP and Stokes vectors obtained through the optimized theoretical model show agreement with the measured ones across all evaluated configurations. This validates the methodology to measure the polarization properties and confirming that the scrambler's depolarization capabilities are highly sensitive to manufacturing tolerances. Higher discrepancies appear in the Stokes vectors when the coefficients are close to zero due to a high measurement uncertainty.

4. CONCLUSION

A comprehensive methodology for polarimetric characterization of commercial crystalline quartz Lyot scramblers intended for space applications has been presented and validated. These components are critical in Earth Observation spectrometers to mitigate the polarization sensitivity induced by atmospheric Rayleigh scattering, which degrades the measurements precision. Although here, it is applied to specific commercial units, the proposed methodology is valid for the evaluation of any type of scrambler. By implementing a polarization state generator and a polarization state analyzer in the set-up, the spatially averaged Stokes vectors and the final degree of polarization at the scramblers' output have been successfully determined.

Measurements of commercial scramblers show a tendency consistent with nominal Code V simulations. The observed discrepancies have been resolved through rigorous optical sensitivity analyses, which led to the conclusion that these discrepancies can be attributed to manufacturing tolerances. Specifically, it has been demonstrated that a slight relative rotation (γ) between the two wedges modifies the orientation of their main optical axes, altering the depolarization capability (DOP) of the scramblers. Furthermore, it has been demonstrated that thickness variations within the tolerance range specified by the manufacturer modify the phase retardation of the scrambler, producing changes in the magnitude and sign of the averaged Stokes parameters in the output.

Finally, an experimental set-up has been developed to measure the degree of polarization at the output of the scramblers, allowing to their comprehensive characterization and subsequent implementation in space spectrometers. This experimental characterization is essential to validate the optical performance of these components and ensure they meet the strict requirements of Earth Observation missions.

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