Design and Measurement of the Stokes polarimeter for the COSMO K-coronagraph

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ABSTRACT

We present the Stokes polarimeter for the new COSMO (COronal Solar Magnetism Observatory) K-coronagraph. The polarimeter can be used in two modes. In observation mode, it is sensitive to linear polarization only and operates as a “Stokes definition” polarimeter. In the ideal case, such a modulator isolates a particular Stokes parameter in each modulation state. For calibrations, the polarimeter can diagnose the full Stokes vector. We present here the design process of the polarimeter, analyze its tolerances with a Monte-Carlo method, develop a way to align the individual elements, and measure and evaluate its performance in both modes.

Subject headings: Instrumentation: polarimeters — Techniques: polarimetric — Sun: corona

1. Introduction

The K-coronagraph (Nelson et al. 2010; Burkepile 2011) is part of the COSMO (the COronal Solar Magnetism Observatory, Tomczyk et al. 2010) facility designed to study the dynamic interaction between the Sun’s magnetic field and plasma in the solar atmosphere. It is specifically tailored to study the formation and propagation of Coronal Mass Ejections (CMEs) that are the primary driver of space weather at Earth. It will measure the polarization brightness (pB) of the K-corona formed by Thomson scattering of photospheric light by coronal free electrons. The COSMO K-coronograph replaces the aging Mauna Loa Mk4 K-coronameter that has been in operation since 1980, which scans the solar corona at a cadence of 3 minutes using a 1-D CCD detector.

Polarized brightness, pB, is defined as the difference between the intensity of light polarized tangentially and radially to the solar limb normalized to the intensity of the solar disk, $B_\odot$, typically given in units of millionths of the disk intensity. It is equal to Stokes $Q$ measured in the reference frame of the solar limb. Assuming that our polarimeter will have a fixed orientation to the sky, then both Stokes $Q$ and $U$ will need to be measured in order to compute $Q$ in the frame of the solar limb. These measurements of three Stokes parameters ($I,Q,U$) require a polarimeter that converts the incoming polarized light into intensities measured by cameras.

The Stokes polarimeter should be designed to have optimal and balanced polarimetric efficiencies for Stokes parameters $I$, $Q$ and $U$ over the operating wavelength range. A so-called “Stokes
are two independent linear polarizations, and the calibration mode should be possible by a simple operation.

In this paper, we present the design of the Stokes polarimeter for the COSMO K-coronograph that satisfies these requirements. The polarimeter consists of a stack of two Ferroelectric Liquid Crystals (FeLCs) and a fixed retarder. The analyzer is a polarizing beamsplitter. The above requirements are achieved by an appropriate choice of orientations and cone angles based on Poincaré sphere and Muller matrix theory (e.g., Shurcliff 1966). In the next section, we summarize the basic design theory of the polarimeter. Then, we analyze the tolerance of the design parameters of the modulator. Finally, the polarimeter is tested and its results are discussed, including a comparison between the theoretical and measured results.

2. Design Theory

Polarized light from the Sun is conventionally described through the Stokes vector $\mathbf{S}_{in} \equiv [I, Q, U, V]^T$, where $I$ is the intensity, $Q$ and $U$ are two independent linear polarizations, and $V$ is the circular polarization. The polarization properties of a Stokes polarimeter in any state can be conveniently described by a $4 \times 4$ Mueller matrix.

Because photon detectors are in practice sensitive only to the intensity, only the first row of the Mueller matrix is important. The modulation of intensity by a $n$-state polarimeter is captured in the $n \times 4$ modulation matrix $\mathbf{X}$. For each state, the corresponding row of the modulation matrix is given by the first row of the Mueller matrix of the polarimeter in that state.

The component choice of the K-coronagraph modulator is driven by the desire to have a static optical setup and a high modulation rate, disqualifying rotating retarders and Liquid Crystal Variable Retarders. A modulator consisting of two FeLCs has four states, the minimum required to allow recovery of the Stokes vector. The polarization analyzer will be a polarizing beam splitter for dual-beam polarimetry. Such a system effectively eliminates crosstalk between $I$ and $Q$, $U$, and $V$. In order to also minimize the crosstalk between $Q$ and $U$, we adopt the choice of a “Stokes definition” modulation scheme, i.e., the modulation matrix $\mathbf{X}$ is given by

$$
\mathbf{X} = \begin{pmatrix}
1 & 1 & 0 & 0 \\
1 & -1 & 0 & 0 \\
1 & 0 & 1 & 0 \\
1 & 0 & -1 & 0 
\end{pmatrix},
$$

(1)

With a modest amount of foresight, we adopt a combination of a 1/2-wave FeLC, a 1/4-wave FeLC, and a 1/4-wave fixed retarder at the central wavelength of 735 nm. For convenience, we refer to the combination of the two FeLCs and the waveplate as ‘the modulator’, the 1/2-wave FeLC as FeLC1, the 1/4-wave FeLC as FeLC2, and the 1/4-wave plate as QWP.

After the polarized light $\mathbf{S}_{in}$ passes through the polarimeter, the intensity $I_m$ measured at the detector will be

$$
I_m = [1, 0, 0, 0] \mathbf{M_A} \mathbf{T}(-\theta_3) \mathbf{R}_{QWP} \mathbf{T}(\theta_3) \times
\mathbf{T}(\theta_2 \pm \Delta) \mathbf{R}_{FeLC2} \mathbf{T}(\theta_2) \times
\mathbf{T}(\theta_1 \pm \Delta) \mathbf{R}_{FeLC1} \mathbf{T}(\theta_1) \mathbf{S}_{in}
$$

$$
= [1, 0, 0, 0] \mathbf{M_A} \mathbf{T}(-\theta_3) \mathbf{R}_{QWP} \mathbf{T}(\theta_3) \times
\mathbf{T}(\theta_2') \mathbf{R}_{FeLC2} \mathbf{T}(\theta_1 - \theta_2') \times
\mathbf{R}_{FeLC1} \mathbf{T}(\theta_1) \mathbf{S}_{in}
$$

(2)

Where, $\theta_2' = \theta_2 \pm \Delta$ and $\theta_1' = \theta_1 \pm \Delta$; $\mathbf{R}_{FeLC1}$, $\mathbf{R}_{FeLC2}$, $\mathbf{R}_{QWP}$ and $\mathbf{M_A}$ are Mueller matrix of FeLC1, FeLC2, QWP and the analyzer, respectively, $\mathbf{T}$ is a rotation matrix, $\mathbf{X}$ is the modulation matrix; $\theta_1$, $\theta_2$ and $\theta_3$ are the orientations of the components; and $\Delta$ is half of the cone angle of the FeLCs. The orientations and cone angle will be determined by Poincaré sphere and Mueller matrix theory below.

In the Poincaré sphere, the $x$, $y$, and $z$ axes represent the $Q$, $U$, and $V$ polarization state, respectively. A rotation matrix $\mathbf{T}$ over an angle $\theta$ is equivalent to a clockwise rotation of $2\theta$ around the $z$ axis, i.e., circular polarization does not change; a retarder Mueller matrix $\mathbf{R}$ with retardation $\delta$ is equivalent to a clockwise rotation of $\delta$ around the $x$ axis, so that linear polarization $Q$ does not...
change. It is easy to see that a 1/2-wave retarder only changes the sign of $U$ and $V$ polarizations but the absolute value of all Stokes parameters are maintained; in comparison, a 1/4-wave retarder will transform $V$ into $U$, and $-U$ into $V$.

Table 1 illustrates the propagation of an input Stokes vector to the output vector $S_m = [I, Q_m, U_m, V_m]^T$ through the elements of the modulator. The FeLCs encode $Q$, $U$, and $V$ into $Q_m$ and $U_m$, $Q$ and $U$, but no $V$, into $V_m$. Only if the combined effect of the QWP and analyzer satisfies $[1, 0, 0, \pm 1]$ will the polarimeter modulate $Q$ and $U$, but not $V$. Simple algebra yields

$$ [1, 0, 0, 0] M_A \mathbf{T}(\theta_3) R_{QWP} \mathbf{T}(-\theta_3) = [1, \cos^2 2\theta_3, \sin 2\theta_3 \cos 2\theta_3, -\sin 2\theta_3]. \quad (3) $$

We conclude that $\cos 2\theta_3$ must be zero to obtain $[1, 0, 0, \pm 1]$, so that the orientation of the QWP is given by

$$ \theta_3 = \pm 45^\circ. \quad (4) $$

The modulation matrix $\mathbf{X}$ is now given by

$$ \mathbf{X} = [1, 0, 0, 0] M_A \mathbf{T}(\theta_3) R_{QWP} \mathbf{T}(-\theta_3) \mathbf{T}(\theta'_2) R_{FeLC2} \mathbf{T}(\theta'_1 - \theta'_2) R_{FeLC1} \mathbf{T}(-\theta'_1) = [1, -\sin(4\theta'_1 - 2\theta'_2), \cos(4\theta'_1 - 2\theta'_2), 0]\quad (5) $$

Where $4\theta'_1 - 2\theta'_2 = 4\theta_1 - 2\theta_2 + [2\Delta_1 - 2\Delta, 6\Delta, -6\Delta]^T$ results from 4 different fast axis positions of the two FeLCs. From this equation it is evident that the orientation of FeLC1 is free to be arbitrarily chosen. A rotation of FeLC1 can be compensated by rotating FeLC2.

There are 24 possible ways to make a correspondence between Eq. 5 and the rows of the modulation matrix. Because of symmetry, there are 12 unique ways, of which only 4 yield a solution that satisfies the condition of the Stokes definition scheme,

$$ -\sin(4\theta_1 - 2\theta_2 + 2\Delta) = \pm 1 \quad \text{and} \quad -\sin(4\theta_1 - 2\theta_2 - 6\Delta) = \mp 1, \quad (6) $$

or

$$ -\sin(4\theta_1 - 2\theta_2 - 2\Delta) = \pm 1 \quad \text{and} \quad -\sin(4\theta_1 - 2\theta_2 + 6\Delta) = \mp 1. \quad (7) $$

We now find

$$ 4\theta_1 - 2\theta_2 + 2\Delta = (k + 1/2)\pi \quad \text{and} \quad 8\Delta = (2l + 1)\pi, \quad k, l \in \mathbb{Z}, \quad (8) $$

or

$$ 4\theta_1 - 2\theta_2 - 2\Delta = (k + 1/2)\pi \quad \text{and} \quad 8\Delta = (2l + 1)\pi, \quad k, l \in \mathbb{Z}. \quad (9) $$

Eliminating $\Delta$ from Eqs. 8 and 9 we have

$$ 4\theta_1 - 2\theta_2 = \left( \frac{1}{4} + \frac{k'}{2} \right) \pi \quad k' = 2k - l \in \mathbb{Z}. \quad (10) $$

We now choose $\theta_1 = 11.25^\circ$. From Eqs. 8, 9, and 10 we then immediately find

$$ \theta_2 = \frac{k'}{4} \pi = [-45^\circ, 0^\circ, 45^\circ, 90^\circ] \quad \text{and} \quad \Delta = \frac{1}{8} \pi = 22.5^\circ, \quad (11) $$

where only the four solutions for $\theta_2$ in the range $[-90^\circ, 90^\circ]$ are given. Any other solution for $\theta_2$ is equivalent to one of these four.

There are 8 configurations for the polarimeter with the following orientations of FeLC2 and QWP: $[-45^\circ, \pm 45^\circ]$, $[0^\circ, \pm 45^\circ]$, $[45^\circ, \pm 45^\circ]$, and $[90^\circ, \pm 45^\circ]$. Fig. 1 shows the predicted modulation efficiencies (del Toro Iniesta & Collados 2000) of Stokes parameters $I$, $Q$, and $U$ in the different schemes between 550 nm and 950 nm. The configurations $[90^\circ, \pm 45^\circ]$ and $[-45^\circ, 45^\circ]$ have the best modulation efficiencies. However, in the polarization calibration of the telescope is desirable to calibrate the cross-talk among $I$, $Q$, $U$, and $V$. The polarimeter must thus have the ability to operate in a full-Stokes mode. Table 1 and Eq. 3 show that this can be achieved by a bulk rotation of $45^\circ$ of the modulator with respect to the analyzer. Fig. 2 shows the modulation efficiency in the calibration mode. The configurations $[90^\circ, \pm 45^\circ]$ have poor efficiency. In contrast, the configuration $[-45^\circ, 45^\circ]$ has excellent efficiency. We note that it is not necessary to pursue very high efficiency in the calibration mode; a somewhat lower efficiency can be compensated by a longer integration time. Based on this analysis, we choose the configuration $[-45^\circ, 45^\circ]$ for the orientation of FeLC2 and QWP. The modulation matrix $\mathbf{X}$ of the polarimeter is shown in Fig. 3.
This design, in addition, is flexible in the sense that any solution from “Stokes definition” to “balanced” modulation can be achieved by adjusting the orientations of the FeLCs.

3. Tolerance Analysis

We employ an iterative Monte-Carlo method to determine the tolerances on the polarimeter design. A statistically large number of modulator matrix realizations are calculated with parameters chosen from normal distributions around the design values. The root sum square (RSS) of the variations of the efficiency from the theoretically ideal values is calculated for each realization. The standard deviations of the distributions of the parameters are reduced iteratively until 90% of the realizations show less than the pre-determined, acceptable reduction in efficiency.

The fraction of samples that meet the requirement is computed from the initial set of realizations. For each parameter, realizations are picked that again from a normal distribution, but with a reduced standard deviation, and the fraction of the new sample that meets the requirement is computed. The spread of the distribution in one parameter is reduced by random choice weighted by the improvement. Because the resampling of the normal distribution is fast, we can choose to have a small reduction in the standard deviation and repeat the procedure many times. The random process ensures that no one parameter is favored. If the number of realizations drops below a predetermined level, a new sample is computed.

The initial widths of the distributions for the parameters are taken either from specifications of the manufacturer of the component, or initialized with generous values intended to steer the optimization toward constructible designs. We stop the iteration for the \((Q,U)\)-only configuration of the modulator once at least 90% of the samples are within 5% of the peak efficiency in an RSS sense. The cumulative distribution function is shown in Fig. 4. Table 2 shows the tolerances expressed as 1-\(\sigma\) standard deviations in degrees. The \((Q,U)\) configuration of the modulator has tighter tolerances. Since this configuration is not intended to be used during regular observations, a more lax condition on the reduction from the peak efficiency can be used. The numbers found in the tolerance analysis of the \((Q,U)\) only configuration yield a better than 90% chance of less than 14% reduction in efficiency in an RSS sense.

The tolerances are not a unique set of conditions that must be satisfied. If, e.g., a component cannot be manufactured to the required accuracy, the tolerances on other parameters may be tightened to still meet the 90% chance of less than 5% reduction in modulator efficiency. Also, once devices have been manufactured and measured, some parameters will be known quantities, and other tolerances could become less strict.

4. Measurement

4.1. Element Alignment

To build the polarimeter described above, it is important to align each element to the right orientation. For the QWP and the analyzer the reference axis is fixed. For these elements the com-
<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Design value (degree)</th>
<th>Tolerance (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeLC1</td>
<td>Retardation</td>
<td>180</td>
<td>±3.0</td>
</tr>
<tr>
<td>FeLC1</td>
<td>Orientation</td>
<td>11.25</td>
<td>±1.0</td>
</tr>
<tr>
<td>FeLC1</td>
<td>Cone angle</td>
<td>45</td>
<td>±2.0</td>
</tr>
<tr>
<td>FeLC2</td>
<td>Retardation</td>
<td>90</td>
<td>±3.0</td>
</tr>
<tr>
<td>FeLC2</td>
<td>Orientation</td>
<td>-45</td>
<td>±1.0</td>
</tr>
<tr>
<td>FeLC2</td>
<td>Cone Angle</td>
<td>45</td>
<td>±2.0</td>
</tr>
<tr>
<td>QWP</td>
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<td>90</td>
<td>±1.5</td>
</tr>
<tr>
<td>QWP</td>
<td>Orientation</td>
<td>45</td>
<td>±1.0</td>
</tr>
</tbody>
</table>

The common aligning method is to place it in between two crossed polarizers. A monochromatic light source is used to send a collimated beam through the three components. A photodiode and an oscilloscope are used to detect the intensity signal. To align the element with the orientation of the polarizers, it is rotated until the output intensity is minimized.

Compared to QWP and analyzer, it is more difficult to align FeLCs because they change the position of their fast axis between two stable positions associated with the positive and negative drive voltage. Rather than to minimize the intensity, we try to find balanced output intensities of the two states of the FeLC. The two intensities can be calculated from the following equations:

\[ I_1 = 1 - \cos^2(2\theta - 2\Delta) - \sin^2(2\theta - 2\Delta) \cos(\delta), \tag{12} \]
\[ I_2 = 1 - \cos^2(2\theta + 2\Delta) - \sin^2(2\theta + 2\Delta) \cos(\delta), \tag{13} \]

where \( \theta \) and \( \delta \) are orientation and retardation of the FeLC. \( \theta \) is the bisector of the two fast axis positions of the FeLC. If the two intensities are equal, we have:

\[ I_1 \equiv I_2 \Rightarrow (1 - \cos(\delta)) \times \]
\[ (\cos(4\theta - 4\Delta) - \cos(4\theta + 4\Delta)) \equiv 0. \tag{14} \]

The FeLC orientation is determined by

\[ \theta = 45^\circ n, \quad n \in \mathbb{Z}. \tag{15} \]

That is, the orientation after alignment suffers from a \( 45^\circ \) ambiguity. Therefore, another waveplate with known retardation \( \delta_1 \) and fast axis orientation, is inserted behind the FeLC and rotated to \( 45^\circ \) with respect to the polarizers. Then, the difference of both intensities \( I_1 \) and \( I_2 \) is as follows

\[ I_1 - I_2 = (\cos(\delta) - 1) \cos \delta_1 \times \]
\[ \left( \cos^2(2\theta + 2\Delta) - \cos^2(2\theta - 2\Delta) \right) + \]
\[ \sin \delta \sin \delta_1 \times \]
\[ \left( \sin(2\theta + 2\Delta) - \sin(2\theta - 2\Delta) \right). \tag{16} \]

If the intensities \( I_1 \) and \( I_2 \) are still balanced, the orientation of the FeLC is parallel to the first polarizer; otherwise, the orientation of the FeLC is \( 45^\circ \) relative to the polarizers.

Note that this technique does not work if the optic under test has exactly \( \frac{1}{2} \)-wave retardance, because in that case the intensities are always equal regardless of the orientation of the waveplate. We purposely choose a light source with a wavelength far from the design wavelength of our devices in order to avoid this issue.

### 4.2. Individual Element Testing

Each component was tested and characterized individually. The Mueller matrices of the individual elements are measured using a lab setup and parameters are fitted from those Mueller matrices. Each element was measured in the ambient temperature of \( 23^\circ \text{C} \), and heated in a small oven to \( 29^\circ \text{C} \) and \( 35^\circ \text{C} \).

The lab setup has a calibration stage consisting of a polarizer and a waveplate in rotation mounts. Light is fed through this stage and through the component under test, through a polarimetric modulator, and finally into a small spectrograph.
Fig. 1.— Modulation efficiency curves for the polarimeter in observation mode between 550 nm and 950 nm. Different curves represent different orientation configurations. In the legend, the two numbers give the orientations of FeLC2 and QWP.

Fig. 2.— Modulation efficiency curves of three configurations of the polarimeter in calibration mode between 550 nm and 950 nm.

Fig. 3.— Modulation matrix \( \mathbf{X} \) of the COSMO K-coronograph polarimeter between 550 nm and 950 nm.

Fig. 4.— Cumulative distribution function of the sample of the modulators used in the tolerance analysis. With the tolerances given in Table 2 there is a 90% probability of less than a 5% decrease in efficiency for the \((Q,U)\) only configuration (solid line) and a 90% probability of less than a 14% decrease in efficiency for the \((Q,U,V)\) configuration (dashed line).
The calibration stage and the polarimetric modulator are used to generate 16 linearly independent input Stokes vectors. Using this system, the full Mueller matrix of the component under test can be determined as a function of wavelength between approximately 550 and 950 nm.

Fig. 5 shows the fitted parameters, including retardation, orientation and cone angle for one set of components. The different curves represent the three temperatures. The cone angles of the FeLCs do not reach the design value of 45 degrees and decrease with increasing operating temperature. We employ the fitted parameters to calculate the modulation efficiencies of Stokes polarimeter in observation mode and calibration mode, as shown in Figs. 6 and 7. Within the temperature range 23°C–35°C, the modulation efficiencies are only minimally affected by the reduced cone angle.

4.3. Testing and characterization

The tests of the individual elements made us confident that the modulator will operate efficiently. Two modulators were built up with air gaps between the elements and tested as a unit. The measured results of the modulation matrix $X$ are shown in Fig. 8 for one of the two units and compared to the theoretical prediction (solid line) as well as the results of the element tests (dotted line). The dashed line indicates the results from the unit test. It is shown in Fig. 8 that the unit results reproduce the results of the element tests closely, but exhibit a large discrepancy from the theoretical prediction. This is likely caused by the difference in cone angle as well as differences between the design and as-built retardations of the modulator optics.

Figs. 9 and 10 show the modulation efficiencies in the observation mode and in the calibration mode, respectively. They are calculated based on the modulation matrix $X$ shown in Fig. 8. The results are similar. Again, the theoretical prediction is significantly off, but the results from the individual element tests closely reproduce the results for the unit. The only difference is that the unit results and the element results show some discrepancy below 600 nm, possibly due to an undetected leak in the interference filter and dichroism of the analyzer used during the measurement in the laboratory, combined with the poor spectral response of the spectrometer below 600 nm.
Fig. 7.— Modulation efficiencies calculated from measured parameters of individual elements in calibration mode. Different curves represent different temperatures, using the same format as in Fig. 5.

Fig. 8.— Comparison of the modulation matrix $X$ in observation mode between 550 nm and 950 nm. Solid line: theoretical prediction; dotted line: results predicted from the measurements of the individual elements; dashed line: measured results.

Fig. 9.— Modulation efficiencies calculated from measured parameters of individual elements in observation mode. The different line styles have the same representation as in Fig. 8.

Fig. 10.— Modulation efficiencies calculated from measured parameters of individual elements in calibration mode. The different line styles have the same representation as in Fig. 8.
After final assembly, the two modulators are tested again to verify modulation efficiency. Over the COSMO K-coronagraph bandpass, the two modulators are found to have \((I,Q,U)\) modulation efficiencies of (99%,70%,72%) and (99%,67%,71%). A perfect modulator would reach (100%,71%,71%). We note that when driven with ±10 V, the \(\frac{\lambda}{2}\)-wave FeLC reaches a cone angle of about 45\(^\circ\), but the \(\frac{\lambda}{4}\)-wave device reaches only about 41\(^\circ\). The efficiency of the modulation is not greatly impacted, but the modulator does not behave strictly as a Stokes-definition type modulator (see Fig. 8).

5. Conclusion

In this paper, we have designed a polarimeter using Poincaré sphere and Mueller matrix theory for the new COSMO K-coronagraph. The polarimeter can be used in two modes. In observation mode, it is sensitive to linear polarization only and operates as a “Stokes definition” polarimeter. In the ideal case, such a modulator isolates a particular Stokes parameter in each modulation state. For calibrations, the polarimeter can measure the full Stokes vector. Conversion from one mode to the other is achieved by a simple bulk rotation of the modulator with respect to the analyzer. The polarimeter design exhibits high efficiency both in the observation mode and in the calibration mode. We employed an iterative Monte-Carlo method to determine the tolerances on the design. We have discussed element alignment and have developed a method to determine the orientations of FeLCs.

Optics were procured for the construction of two modulators. We measured the Mueller matrices of the individual elements at different temperatures, and determined the modulation efficiency of Stokes polarimeter based on the fitted element parameters. We found that the modulation efficiency is almost constant in the temperature range 23°C–35°C. Finally, we measured the real modulation matrix \(X\) of the polarimeter, and calculated modulation efficiencies in observation and calibration mode. These measured results are compared with the theoretical predictions and the ones based on the fitted element parameters. The measured results are shown to be in close agreement with the results based on the fitted element parameters. We conclude that it is possible to assess the real performance of a Stokes polarimeter by measuring the Mueller matrices of the individual elements.

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