COSMO Large Coronagraph Polarimetry Requirements

Steven Tomczyk and Alfred deWijn

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1 INTRODUCTION

This document presents the plan for performing polarimetry with the COSMO Large Coronagraph. This includes a discussion of the requirements for the polarimetry, the design of the polarimeter, and the methodology for its calibration.

1.1 REFERENCE DOCUMENTS

1. COSMOLC-RQ-1000 Science Requirements Document
2. COSMOLC-RQ-1001 Concept of Operations
3. COSMOLC-RQ-6000 Instrument Science Requirements Document
4. COSMOLC-RQ-6010 Telescope Requirements Document
5. COSMOLC-RQ-6011 Filtergraph Requirements Document
6. COSMOLC-RQ-6001 Interface Control Chart
7. COSMOLC-PL-8002 Calibration Plan
8. COSMOLC-PL-8000 Science Verification Plan
9. COSMOLC-PL-8100 Compliance Matrix
10. COSMOLC-MG-2000 Management Plan
2 THE COSMO LC POLARIMETER

The design of the polarimeter for the COSMO LC is based on recent work on wavelength diverse polarization modulators (Tomczyk et al., 2010) where the modulator is found by optimizing the polarimetric efficiency across all wavelengths of interest. These modulators are not achromatic in the usual sense because their polarimetric properties vary with wavelength. But they are optimal in terms of maximizing the S/N ratio of the polarimetric measurement. We refer to these modulators as *polychromatic*. The definition of polarimeter efficiency upon which this work is based can be found in del Toro Iniesta and Collados (2000). The efficiency is important in that the noise in a Stokes parameter is inversely proportional to the efficiency of the polarimeter for that parameter at that wavelength. Therefore, high polarimetric efficiency results directly in higher S/N ratio. The maximum efficiency for a modulator that modulates all Stokes parameters and has balanced efficiency for Q, U and V is unity for Stokes I and 0.577 for Q, U and V. For COSMO the goal is to have the Stokes Q, U and V efficiencies greater than 0.5 over the filtergraph wavelength range of 530 to 1083 nm.

The proposed polarization modulator for the COSMO LC is a continuously rotating compound waveplate followed by a polarizing beamsplitter. It is a dual-beam polarimeter. The waveplate is comprised of two polymer retarders. The retardations and orientations of the fast axes of the retarders are given in Table 1. The optimization routine assumes the analyzer is an ideal polarizer.

<table>
<thead>
<tr>
<th>Material</th>
<th>Retardation (waves @ 22°C)</th>
<th>Orientation (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>polymer</td>
<td>0.240</td>
</tr>
<tr>
<td>2</td>
<td>polymer</td>
<td>0.282</td>
</tr>
</tbody>
</table>

Figure 1 shows the polarimetric efficiency for the polarimeter as a function of wavelength for the four Stokes parameters. It assumes images are taken every 22.5 degrees of rotation of the rotating waveplate. A modulation cycle is comprised of 8 image acquisitions taken over a half-rotation of the waveplate. Then, 16 images will be taken during every revolution of the waveplate. The integration time is assumed to be 1/16 of the rotation time. All 8 images will be required to compute the Stokes parameter input into the polarimeter. The boxes in Figure 1 indicate the wavelengths at which the solution was optimized.

We conducted a tolerance analysis to investigate the sensitivity of the polarimeter to inaccuracies in the fabrication of the modulator components. We assumed a 1 sigma tolerance of 1/350 waves retardation (following the specifications for Meadowlark precision retarders) and 0.5 degree fast axis orientation tolerance. The efficiencies for the Stokes parameters over the wavelength range were calculated for 10,000 realizations using normally distributed errors on the retardation and orientation. The efficiencies for each Stokes parameter and wavelength were sorted and the 2 sigma tolerance was defined as the efficiency of the worst case after rejecting the worst 5% of the realizations. The 3 sigma tolerance was defined as the efficiency of the worst case after rejecting the worst 0.3% of the realizations.

The results of the tolerance analysis are shown in Figure 2. The top curves on each plot represents the zero error case (the same as Figure 1) the middle curves show the 2 sigma tolerance efficiencies and the bottom curves show the 3 sigma tolerance efficiencies. The 3 sigma efficiency remains above the goal of 0.5 for Q, U and V over the entire filtergraph wavelength range of interest.
Figure 1 Plots of the polarimetric efficiency of the COSMO polarimeter as a function of wavelength for the Stokes parameters. The boxes indicate the wavelengths for which the solution was optimized.
The polarimeter for the COSMO LC is a critical component to allow the measurement of magnetic fields in the corona at a level of 1 G. To do this, we will observe the Zeeman effect in the FeXIII 1074.7 nm coronal emission line. The sensitivity of the measurement is set by the amplitude of the Stokes V signal as a fraction of the line central intensity. The 1 G requirement translates into a $10^{-4}$ polarimetric precision requirement (1.3·$10^{-5}$ from Tomczyk, 2015, COSMO TN #1). This is distinct from the polarimetric accuracy requirement which will be derived in the following.

The basic equation governing the measurement of polarization is

$$S' = X S$$
where $S'$ is the measured 4-element Stokes vector, $S$ is the actual Stokes vector and $X$ is the 4x4 transformation matrix defining the measurement process. For an ideal polarimeter, $X$ has values of 1 along the diagonal and 0 everywhere else. The $X$ matrix can be written in terms of the $I, Q, U, V$ Stokes parameters as

$$X = \begin{bmatrix} I > I & Q > I & U > I & V > I \\ I > Q & Q > Q & U > Q & V > Q \\ I > U & Q > U & U > U & V > U \\ I > V & Q > V & U > V & V > V \end{bmatrix}$$

where the diagonal terms are scaling terms set by the polarimetric efficiency. The off-diagonal elements of $X$ represent “crosstalk” in the measurement process. The $X$ matrix is commonly normalized by the $I > I$ element.

The calibration process is required to determine the values in the $X$ matrix and the desired accuracy on the matrix elements sets the polarimetric accuracy requirement. We draw on two excellent references for polarimeter calibration, that for the Advanced Stokes Polarimeter (Elmore, 1990) and for the Solar Optical Telescope on Hinode (Ichimoto et al., 2008). Ichimoto et al. have determined that the required accuracy on the $X$ matrix elements (the error matrix) is

$$\Delta X = \begin{bmatrix} -a/p_L & a/p_L & a/p_C \\ \varepsilon & \varepsilon/p_L & \varepsilon/p_C \\ \varepsilon & \varepsilon/p_L & \varepsilon/p_C \\ \varepsilon & \varepsilon/p_L & \varepsilon/p_C \end{bmatrix},$$

where $\varepsilon$ is the desired photometric precision, $p_L$ is the maximum linear polarization, $p_C$ is the maximum circular polarization and $a$ is the allowable scale error. For the COSMO LC, we estimate

$$\varepsilon = 10^{-4}$$ (to meet 1 G magnetic field error),
$$a = 0.05$$ (following Ichimoto et al.),
$$P_L = 0.1,$$
$$P_C = 10^{-3}$$ (corresponding to 10 G).

This results in

$$\Delta X = \begin{bmatrix} - & 0.50 & 0.50 & 50.0 \\ 10^{-4} & 0.05 & 10^{-3} & 0.10 \\ 10^{-4} & 10^{-3} & 0.05 & 0.10 \\ 10^{-4} & 10^{-3} & 10^{-3} & 0.05 \end{bmatrix}.$$

The expected Stokes $V$ signal is so small that $V > I, Q, U$ is not important. The required accuracy on the diagonal sensitivity terms is also not severe. The $I > Q, U, V$ terms represent the biggest challenge.

It is significant that the LOS magnetic field is inferred by the amplitude of the Stokes $V$ signal across the line profile. The $V$ profile is proportional to the first derivative of the intensity with wavelength so the $V$ profile is anti-symmetric around line center. The line profiles of Stokes $Q$ and $U$ are proportional to the profile of Stokes $I$ so that $I, Q$ and $U$ are all symmetric around line center. This allows one to measure the Stokes $V$ signal in the presence of significant crosstalk from $I, Q$ and $U$ into $V$. This technique has been successfully demonstrated by Lin, Kuhn and Coulter (2004) who measured the LOS magnetic field in the presence of crosstalk of $I > V = 3\%$, $Q > V = 9\%$ and $U > V = 16\%$. We reproduce Figure 5 from their paper in our Figure 3 to illustrate that they were able to obtain the amplitude of the $V$ signal at a level at or below $10^{-4}$. We argue that the $I, Q, U > V$ terms along the bottom row of the error matrix do not need to be so tightly constrained, and set the requirement on these elements to be 0.01.
It is common practice to correct $I > Q, U, V$ crosstalk in photospheric spectro-polarimetry data using the fact that the continuum is unpolarized (e.g. see Lites and Ichimoto, 2013). In the corona, the continuum is linearly polarized by electron scattering, but the brightness of the K-corona falls off rapidly from a value of about $10^{-6}$ at the limb to value around $10^{-8}$ at the edge of the LC field-of-view (van de Hulst, 1950). We believe that we will be able to determine the $I > Q, U$ crosstalk coefficients from the data itself by looking in the continuum where the K-corona is weak or absent. Therefore, we set the accuracy requirement on these matrix elements to be $10^{-3}$.

On the basis of this reasoning, the revised accuracy requirement on the $X$ matrix elements is

$$
\Delta X = \begin{bmatrix}
- & 0.50 & 0.50 & 50.0 \\
10^{-3} & 0.05 & 10^{-3} & 0.10 \\
10^{-3} & 10^{-3} & 0.05 & 0.10 \\
0.01 & 0.01 & 0.01 & 0.05
\end{bmatrix},
$$

and we adopt a polarimetric accuracy requirement of $10^{-3}$ for the COSMO LC. The next section presents the methodology for calibrating the instrument at this level.

### 4 POLARIZATION CALIBRATION METHODOLOGY

To calibrate the LC polarimeter, we will adopt standard practices. The LC will have a calibration unit with a polarizer and retarder that can be inserted into the beam. These optical elements can be inserted independently and rotated to any angle. The calibration unit will be approximately 1 meter in front of the occulting disk. The diffuser will be inserted into the beam for all calibrations. It is located between the O1 polarization and calibration optics.
The calibration unit will calibrate the polarimeter and all optics between the calibration unit and the polarimeter. It cannot calibrate any polarization introduced by the objective lens. The polarization effects due to reflections by the uncoated O1 across the COSMO field-of-view were calculated by Elmore (2006) who found that the off diagonal elements were less than $10^{-7}$. Birefringence in the COSMO O1 was modeled with finite element analysis by Nelson (2006). He found that the stress birefringence in the lens introduced off diagonal elements in the Mueller matrix of the lens at a level of less than $10^{-4}$. We will check the polarization and retardation introduced by the objective lens by mounting an array of polarizers in front of the objective lens during commissioning to verify the properties of the objective lens and any variation with zenith angle.

To meet the calibration accuracy requirement, the Mueller matrix of the calibration optics must be known to some degree. For the calibration polarizer, knowledge of the Mueller matrix elements must be known to the accuracy requirement of $10^{-3}$ for all wavelengths of interest. This is not the case for the calibration retarder. Experience has shown that the retardation of the calibration retarder is determined during the calibration process. This is because the calibration retarder is rotated between the calibration polarizer and the polarimeter. However, any deviations of the calibration retarder Mueller matrix from that of an ideal retarder must be known at the $10^{-3}$ level.

This level of calibration has been met by a number of instruments. It is very advantageous to the success of the calibration of the polarimetry for the COSMO LC that the optical system is completely on axis with no reflections.

The following subsections further describe the calibration procedure with derived requirements.

### 4.1 CALIBRATION OPTICS ANGULAR CALIBRATION

**Requirement.** The absolute position of the calibration polarizer and retarder with respect to the polarization modulator must be known to better than 0.1 degree for the calibration procedure.

**Procedure.** With the modulator out of the beam but the polarization analyzer (beam splitter) still in the beam, the calibration polarizer will be driven to its home position, and then driven around a full rotation. The angular positions of minimum and maximum transmission are the absolute positions on which the calibration polarizer is crossed and parallel to the polarization analyzer, respectively. With the calibration polarizer oriented to the axis of one of the beams of the analyzer, the calibration retarder is inserted in the beam and driven around a full rotation. The maximum and minimum transmission angles define the axis of the retarder.

**Frequency.** This calibration will be performed during testing and commissioning of the instrument, and after changes to polarization analyzer.

**Verification.** The procedure will be repeated several times to verify the accuracy of the measurement.

### 4.2 CALIBRATION OPTICS MUELLER MATRIX CALIBRATION

**Requirement.** The Mueller matrix for the calibration polarizer and retarder needs to be known to the polarimetric accuracy requirement of $10^{-3}$. The retardance of the retarder does not need to be determined, only deviations from the Mueller matrix of an ideal retarder.

**Procedure.** The Mueller matrices of the calibration polarizer and retarder must be determined in the lab with a calibrated spectropolarimeter.

**Frequency.** This calibration will be performed before commissioning of the instrument.

**Verification.** The procedure may be repeated periodically to verify the accuracy of the measurement.
4.3 **Polarimetric Calibration**

**Requirement.** The polarization modulator must be calibrated to meet the polarimetric sensitivity requirement of $10^{-3}$.

**Procedure.** The procedure is described in the following sections.

**Frequency.** Initially, at least one calibration will be taken per day, with 2 calibrations being a goal. Observers will run calibrations during good sky conditions.

**Verification.** Two or more calibrations will be taken in quick succession and compared for discrepancies. The telescope model will be used to simulate the calibration.

4.4 **Polarization Calibration Sequence**

A calibration sequence consists of 5 types of image sets consisting of the 8 modulation states:

1. Dark: dark shutter closed.
2. Clear: diffuser in the beam, calibration optics out.
3. Polarization calibration: diffuser and calibration polarizer in the beam, calibration polarizer rotated to 0, 45, 90, and 135 degrees with respect to the analyzer.
4. Polarization calibration: diffuser, calibration polarizer and calibration retarder in the beam, calibration polarizer rotated to 0, calibration retarder at +/- 45 degrees with respect to the polarizer.
5. Polarization calibration: diffuser and calibration retarder in the beam, calibration retarder rotated to 0, 45, 90, and 135 degrees with respect to the analyzer.
6. The goal is to obtain the calibration sequence in less than 10 minutes.

4.5 **Polarimetric Calibration Data Reduction**

Polarimetric calibration data reduction algorithms have been developed by Elmore (1990), Ichimoto et al. (2008) and others. We will not repeat the details of their algorithms here except to say that the calibration data will be fit with a model of the polarimeter and the unknowns will be solved for. The unknowns include the 15 elements of the normalized response matrix, the input Stokes vector, and the retardance of the calibration retarder.
5 REFERENCES


vanVleck, J.H., 1925, On the Quantum Theory of the Polarization of Resonance Radiation in Magnetic Fields, PNAS, 11, 612.