Polarimetric Characterization of a Model of the Multi Angle Polarimeter for the CO2M Mission

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1 Introduction

In this Technical Report we describe the polarimetric characterization and the Mueller matrix measure of a model of the Multi Angle Polarimeter of the CO2M Mission, in particular of its telescope optical assembly. The measurements were performed in October 2022, in the optics laboratory of the Osservatorio Astrofisico di Torino.

The CO2M mission, part of the Copernicus Expansion programme, will measure anthropogenic CO_2. The Multi Angle Polarimeter (MAP) is part of the instrument suite. The optical design consists of two spherical mirrors arranged in an off-axis Schwarzchild configuration, with a square field of view of $\sim 28^{o} \times 28^{o}$ (see [?]).

The technique used for the measure of the Mueller matrix is the Dual Rotating Retarder Mueller Spectro-Polarimeter (DRRP) technique, which has been originally proposed by [?], and is based on the encoding of the Mueller matrix elements in a signal modulated by two retarders (quarter waves in the present approach), placed before and after the sample, and rotating in a 1:5 ratio.

The advantage of this method is the possibility of a complete measure of the Mueller matrix of the sample, allowing to evaluate deviations from the ideality, such as diattenuation and depolarization. The analysis formalism has been developed by [?], and with a major emphasis on the setup systematic errors by [?] and [?].

The output signal from the MSP has a period of 180^{o}, so after a complete rotation of the first quarter wave the information is redundantly encoded a second time. The frequency analysis of data can be performed with the Fast Fourier Transform technique, or equivalently we can use a least square method to fit the signal (see [?]):

$$s_{out}(q) = I_q = \frac{a_0}{2} + \sum_{n=1}^{12} [a_n \cos(2n\gamma q) + b_n \sin(2n\gamma q)]$$

where q is the progressive number of the measures, a_n and b_n are the Fourier coefficients to be determined, which are functions of the 16 Mueller matrix elements of the sample. The systematic errors in the alignment of the setup components, *i.e.* the two quarter waves and the output polarizer (the transmission axis of the first polarizer defines the reference system), and the deviation of the retardances of the plates from the nominal value, can be evaluated performing a series of measures with no sample (air), with the constrain for the resulting Mueller matrix of the sample to be unitary.

2 Experimental Setup

2.1 Setup Description

The laboratory setup consists of a monocromatic led source Prizmatix at 620 nm, a light guide coupled with a optical fiber, and a collimator. Collimated light is fed into a box ensuring the light tightness and containing the polarimetric components of the setup and the sample to be tested. A first linear polarizer defines the polarization axis of the input radiation. Owing to the low levels from the light source, a PMT has been used as a detector. The stability of the source has been monitored by a second detection channel, in which a photodiode is fed by a beam splitter put after the input linear polarizer. The sample is mounted between two rotating quarter waves, modulating the signal, which is then analyzed by a second linear polarizer and recorded by the PMT. This measurement scheme is also referred to as Mueller Spectro-Polarimeter (MSP), owing to the fact that the sample properties could also be studied as a function of the wavelength (in the present report only the 620 nm wavelength has been used).

The part of the setup from the sample down to the measure PMT, comprising the MAP telescope, the second QW and the analizer PL, has been mounted on a two-axis rotator, in order to characterize the field of view in-axis and off-axis. The rotator has been assembled with two Standa Motorized Rotation Stage 8MR190-2, mounted in a two ortogonal axis configuration (see Figure 2), with a resolution of 4.5 arcsec.

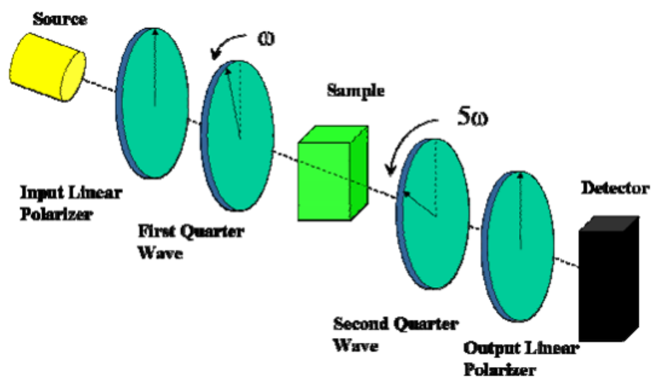

Figure 1: Schematic view of the Mueller Spectro-Polarimeter setup.

Polarimetric components

- Input Linear Polarizer: UVCS n.3
- First Quarter Wave: Meadowlark H3051
- Second Quarter Wave: Meadowlark H3050
- Output Linear Polarizer: UVCS n.1

Mechanical Rotators Rotation Stage PI model M-038.DG

- QW1: Serial number 1379
- QW2: Serial number 1378

Controllers

- Precision Motor Controller PI model C-84420, serial 5000111
- D2040 Meadowlark

Detectors PMT Hamamatsu, model H7155-21

- main channel: n.54690010
- secondary control channel: n.56320009

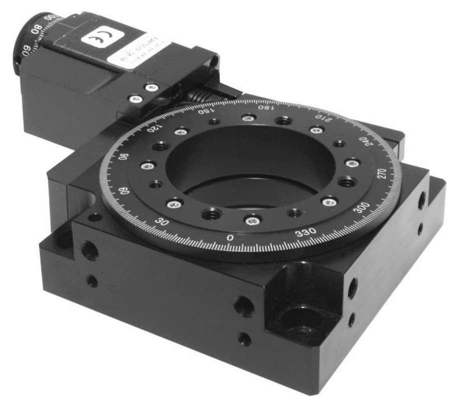

Figure 2: Standa Motorized Rotation Stage 8MR190-2.

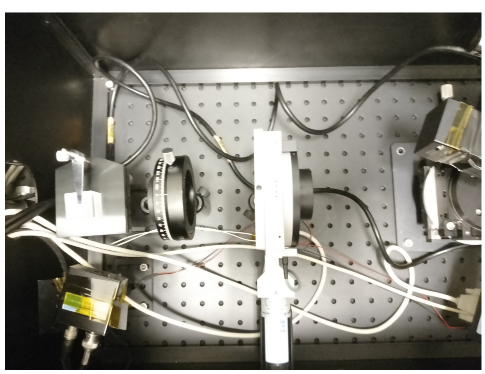

Figure 3: Experimental setup: the MSP assembly.

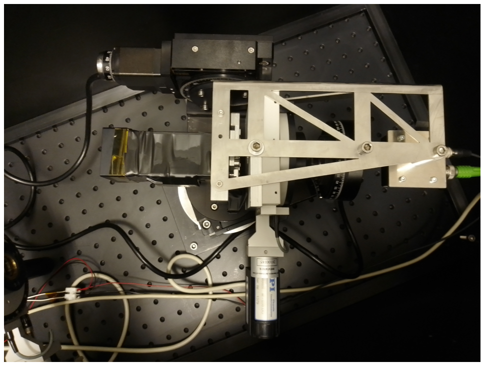

Figure 4: Experimental setup: the two-axis positioner.

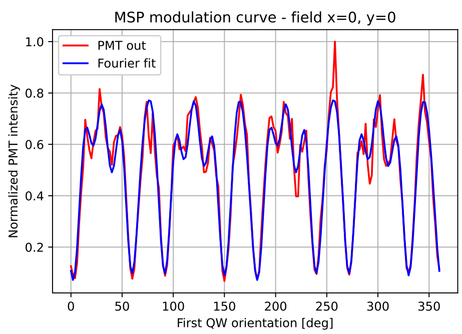

Figure 5: Least square fit of the Mueller matrix Fourier coefficients for the in-axis field.

3 MSP data acquisition

Data have been acquired with the setup shown in Figures (3) and (4). Two fields of the sample have been measured, the central field at 0^o and a field 1^o off-axis. The normalized modulated signal is shown in Figures (5) and (6), for the in-axis and off-axis fields, respectively.

File *Led 3 2000 DN-20221014-133206.data* contains data taken on the day 2022/10/14, h 13:32:06, with step of 2^o, from 0^o to 360^o of the first QW retarder, for a total of 181 experimantal points. The telescope field is the central one: $x = 0, y = 0$. The LED source was used at power corresponding to 2000 DN, in a range from 0 to 4096.

The fit of the Fourier coefficients gives the following Mueller matrix for the field in axis:

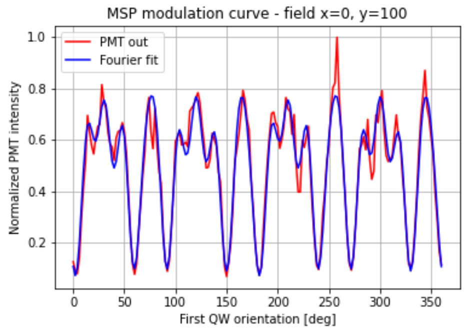

Figure 6: Least square fit of the Mueller matrix Fourier coefficients for the 1 degree off-axis field.

$$M(x=0,y=0)=\begin{pmatrix} 1. & -0.07642 & -0.05168 & 0.00456 \\ -0.18332 & 1.06678 & 0.05815 & -0.01799 \\ -0.03010 & -0.08158 & 1.03072 & 0.10844 \\ -0.02660 & 0.04252 & -0.07062 & 0.86048 \end{pmatrix}$$

File *Led 3 2000 DN-20221014-130616.data* contains data taken on the day 2022/10/14, h 13:06:16, with step of 6°, from 0° to 360° of the first QW retarder, for a total of 611 experimantal points. The telescope field is 1 degree off-axis in the horizontal direction: $x = 0, y = 100$. The LED source was used at power corresponding to 2000 DN, in a range from 0 to 4096.

Mueller matrix elements for the field in 1 degree off-axis in the horizontal direction:

$$M(x=0,y=100)=\begin{pmatrix} 1. & -0.12747 & -0.09312 & 0.07767 \\ -0.19792 & 1.13217 & 0.08516 & -0.11218 \\ -0.09546 & -0.05087 & 1.03921 & 0.10400 \\ 0.08130 & 0.10149 & -0.08483 & 0.80545 \end{pmatrix}$$

3.1 Measure of the linear and circular polarization introduced by the sample telescope

The purpose of the MSP analysis was to measure the presence of spurious linear or circular polarization, introduce by the MAP instrument itself. This was accomplished by fitting the Mueller matrix coefficients to models of a linear or a circular diattenuator. In other words, we check if the results are compatible, and to what degree, with a neutral polarizing element, *i.e.* non introducing linear or circular polarization.

A diattenuator is defined as a medium showing anisotrope attenuation, depending on the polarization status of the incoming radiation. The *diattenuation* D of a system, not depolarizing, is defined as the contrast between the maximum and the minimum coefficients of intensity, respectively p_1^2 e p_2^2:

$$D \equiv \frac{p_1^2 - p_2^2}{p_1^2 + p_2^2}$$

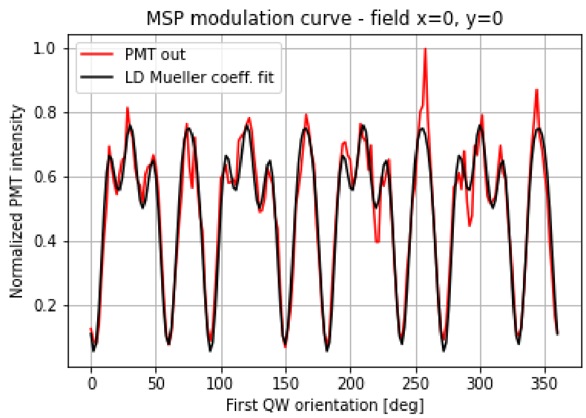

Figure 7: Least square fit of the Mueller matrix coefficients as a linear diattenuator. Field in-axis.

We are referring to a *linear diattenuator* or a *linear partial polarizer* when the eigen-states of the normal diattenuator are linearly polarized. If we write the diattenuation as $D \equiv \cos\kappa$, from which we have $\sin\kappa = \sqrt{1-D^2}$, the Mueller matrix of the medium can be written:

$$M_{DL}(\phi, p_1, p_2) = \frac{p_1^2}{1+\cos\kappa} \times$$
$$\times \begin{pmatrix} 1 & \cos\kappa\cos 2\phi & \cos\kappa\sin 2\phi & 0 \\ \cos\kappa\cos 2\phi & \cos^2 2\phi + \sin\kappa\sin^2 2\phi & \sin 2\phi\cos 2\phi & 0 \\ \cos\kappa\cos 2\phi & \sin 2\phi\cos 2\phi & \sin^2 2\phi + \sin\kappa\cos^2 2\phi & 0 \\ 0 & 0 & 0 & \sin\kappa \end{pmatrix}$$

We are referring to a *circular diattenuator* when the eigen-states are circularly polarized, left or right. The Mueller matrix of such a medium is:

$$M_{DL}(p_1, p_2) = \frac{p_1^2}{1+\cos\kappa} \begin{pmatrix} 1 & 0 & 0 & \cos\kappa \\ 0 & \sin\kappa & 0 & 0 \\ 0 & 0 & \sin\kappa & 0 \\ \cos\kappa & 0 & 0 & 1 \end{pmatrix}$$

4 MSP data analysis. In axis data

The two-axis rotation assembly made difficult the calibration of the MSP without sample, as it implied a translation of the optical axis when the sample was mounted. For this reason we decided to leave the calibration angles as free parameters to be fitted directly in the modulation curve of the sample. In the following the alingnment angle of the two QW and the analizer LP are ϵ_3, ϵ_4, and ϵ_5; δ is the QWs retardance.

4.1 Test as a linear diattenuator

This analysis shows that the introduced linear polarization $D = \cos\kappa$ is not larger than 0.02%.

Parameter	Value [deg]	Error [deg]
ϵ_3	56.9	0.6
ϵ_4	23.0	1.3
ϵ_5	-2.9	1.5
δ	83.8	1.5
α	87.8	1.3
κ	90.2	1.5

Table 1: Parameters of the fit as a linear diattenuator. Field in-axis.

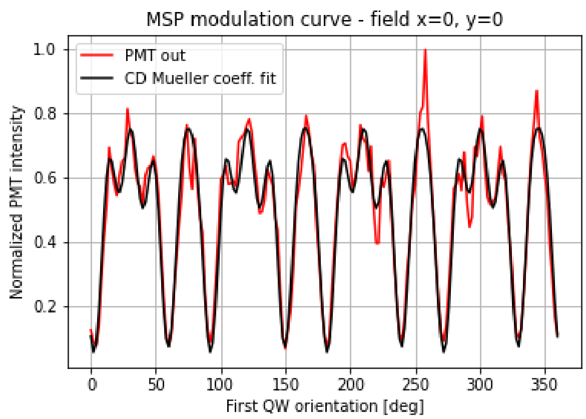

Figure 8: Least square fit of the Mueller matrix coefficients as a circular diattenuator. Field in-axis.

4.2 Test as a circular diattenuator

This analysis shows that the introduced circular polarization $D = \cos\kappa$ is not larger than 0.01%.

5 MSP data analysis. Off axis data

The direction sampled in the telescope field is 1 degree off axis, in the plane of the horizontal positioner, corresponding to $x = 0, y = 100$ microsteps. The LED source was used at power corresponding to 2000 DN, in a range from 0 to 4096.

Parameter	Value [deg]	Error [deg]
ϵ_3	56.3	0.5
ϵ_4	23.4	1.3
ϵ_5	-2.8	1.5
δ	83.7	1.3
κ	89.9	0.6

Table 2: Parameters of the fit as a circular diattenuator. Field in-axis.

5.1 Test as a linear diattenuator

The results of test for the off-axis data as a linear diattenuator are shown in Figure 8 and summarized in Table 3.

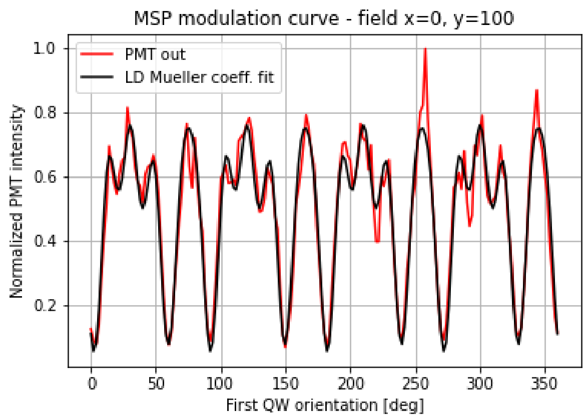

Figure 9: Test as a linear diattenuator. Field off-axis.

Parameter	Value [deg]	Error [deg]
ϵ_3	56.9	0.6
ϵ_4	23.0	1.4
ϵ_5	-2.9	1.6
δ	83.9	1.5
α	87.9	1.3
κ	90.3	1.6

Table 3: Parameters of the fit as a linear diattenuator. Field off-axis.

5.2 Test as a circular diattenuator

The results of test for the off-axis data as a circular diattenuator are shown in Figure 9 and summarized in Table 4.

Parameter	Value [deg]	Error [deg]
ϵ_3	57.3	0.6
ϵ_4	23.5	1.4
ϵ_5	-2.8	1.6
δ	83.8	1.3
κ	89.9	0.7

Table 4: Parameters of the fit as a circular diattenuator. Field off-axis.

The results for the off-axis field are compatible with those obtained for the in-axis field, both for the linear attenuator and the circular attenuator tests.

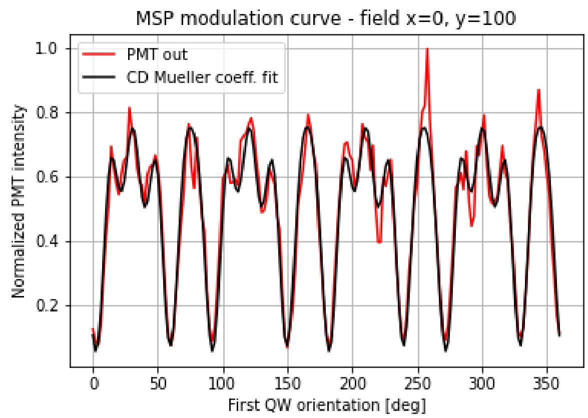

Figure 10: Test as a circular diattenuator. Field off-axis.

6 Conclusions

The analysis of the MSP data shows that the spurious linear or circular polarization introduced by the MAP instrument is within the acceptable limit of 2%, for the in-axis and the off-axis fields which have been sampled.