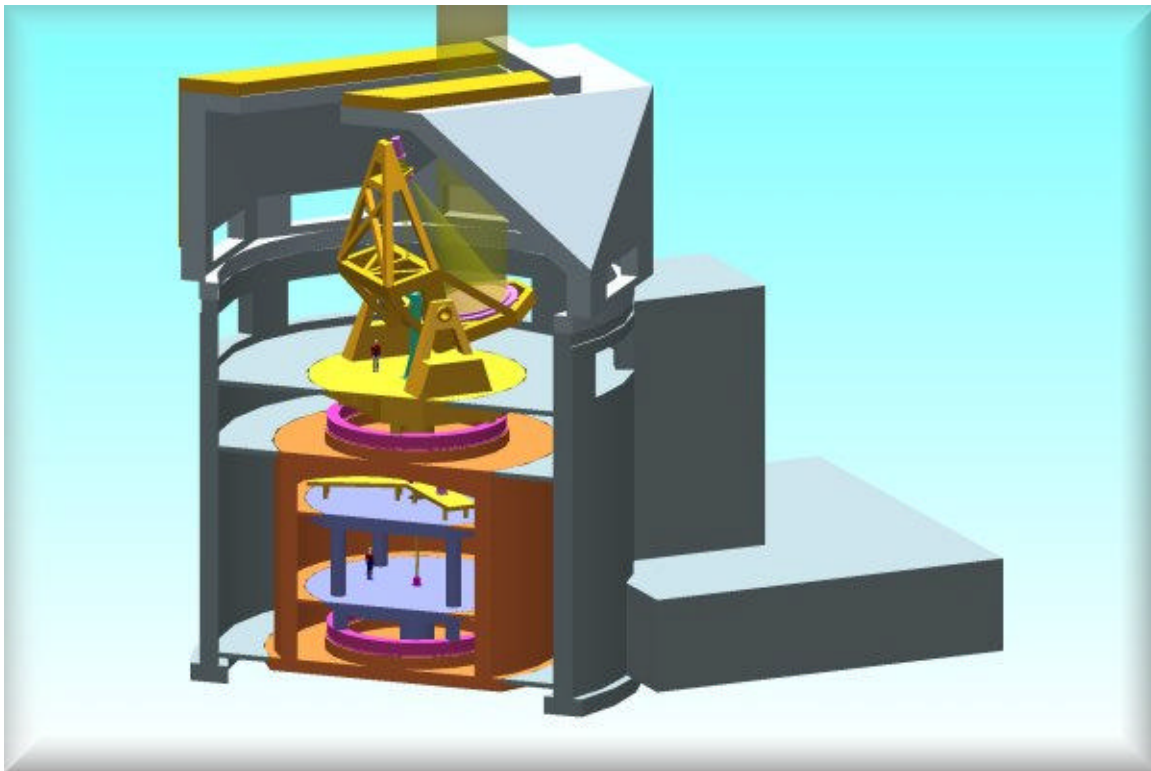


Instrumental Polarization of the Off-Axis Telescope



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Table Of Contents

1. Introduction.....	1
2. Polarized Ray-Tracing	1
3. Mueller Matrices	3
3.1 Primary Mirror F-ratio.....	3
3.2 Wavelength Variation for f/2 Primary Mirror	4
3.3 Field-of-view Variation for f/2 Concept.....	4
4. Conclusions	5

1. INTRODUCTION

While polarimeters are often considered as being pure post-focus instruments on nighttime telescopes and most existing solar telescope, accurate solar polarimetry, as required by the scientific goals of ATST, mandates that polarimetry post-focus instrumentation and the telescope be designed as a system. All optical elements, and in particular mirrors with oblique reflections inside the telescope change or even produce polarization. This artificially introduced polarization is often many orders of magnitude larger than the expected solar signal.

To measure solar polarization accurately, it is important to minimize the instrumental polarization. Although the latter can be determined quite accurately, instrumental polarization often couples with other instrumental effects such as unknown offsets and non-linearities in detectors. As a rule of thumb, it is very hard to measure polarization accurately at levels below one percent of the instrumental polarization. Modern observations of polarized light from the sun often work at that level, which requires instrumental polarization levels below the 1% level as stated in the Science Requirements Document.

The most likely optical configuration of the ATST is an off-axis Gregorian. Such a telescope would not feature axially symmetric optics in front of the location where the polarization analysis is performed due to the oblique reflections off the primary and secondary mirrors. The choice of coating and the diameter of the primary parent have a considerable influence on the amount of instrumental polarization. An off-axis design therefore needs to be particularly well studied in terms of accurate polarimetry.

The following sections provide quantitative predictions of the Mueller matrices for a variety of configurations. Section 2 provides a short overview of the methods used, while section 3 presents the Mueller matrices. Section 4 concludes with a discussion of on vs. off-axis performance and a comparison with other telescopes and concepts such as THEMIS and LEST.

2. POLARIZED RAY-TRACING

The influence of optical elements on the polarization of light is conveniently written in a matrix formalism involving the Stokes vector to describe polarized light and the so-called Mueller matrices to describe the optical elements. The Stokes vector

$$\vec{I} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

describes polarized light, where I is the intensity, Q the difference of the linearly polarized components at 0 and 90 degrees, U the difference of the linearly polarized components at 45 and 135 degrees, and V the difference of left and right circularly polarized light.

The Mueller matrices are real 4 by 4 matrices that operate on Stokes vectors, i.e.

$$\vec{I}' = \mathbf{M} \vec{I}$$

where I is the input Stokes vector, \mathbf{M} the Mueller matrix, and \vec{I}' the output Stokes vector. An optical element with a diagonal Mueller matrix will not mix the various components of the Stokes vector. Any

off-diagonal element, however, describes the mixing (or cross-talk) of polarization components in the Stokes vector. In the following the term *instrumental polarization* will always refer to these off-diagonal elements.

The true instrumental polarization of ATST will be determined by the optical properties of the actual coating, which can only be predicted to within certain accuracy. It therefore does not make sense to try to predict the polarization performance of ATST to better than about a factor of 2. In principle, one could determine the Mueller matrix for each point in the point-spread function (PSF) for all possible locations within the field-of-view. This is a very demanding task and also requires knowledge of the optical aberrations of the system. This is not needed at the present time. Therefore, a much simpler approach has been chosen where the Mueller matrix is calculated and averaged over the PSF for the center of the field-of-view.

The Mueller matrix corresponding to measurements that average over the PSF is the (incoherent) superposition of the Mueller matrices of the individual rays. This is a direct consequence of energy conservation between pupil plane and image plane. Optical aberrations and diffraction are therefore neglected. All calculations have been performed with PolTrace, a JAVA-based program developed for calculating polarization optics. It can import ZEMAX files.

The Mueller matrices in the following sections do not take into account the general absorption upon reflections because solar observations are almost always relative and not absolute measurements. However, the full effect of reflection on a metal surface onto polarization is considered here. The coordinate system for the linear polarization has been chosen such that Stokes Q is parallel to the plane of symmetry.

Instrumental polarization typically increases with the square of the inclination on the reflective surface.

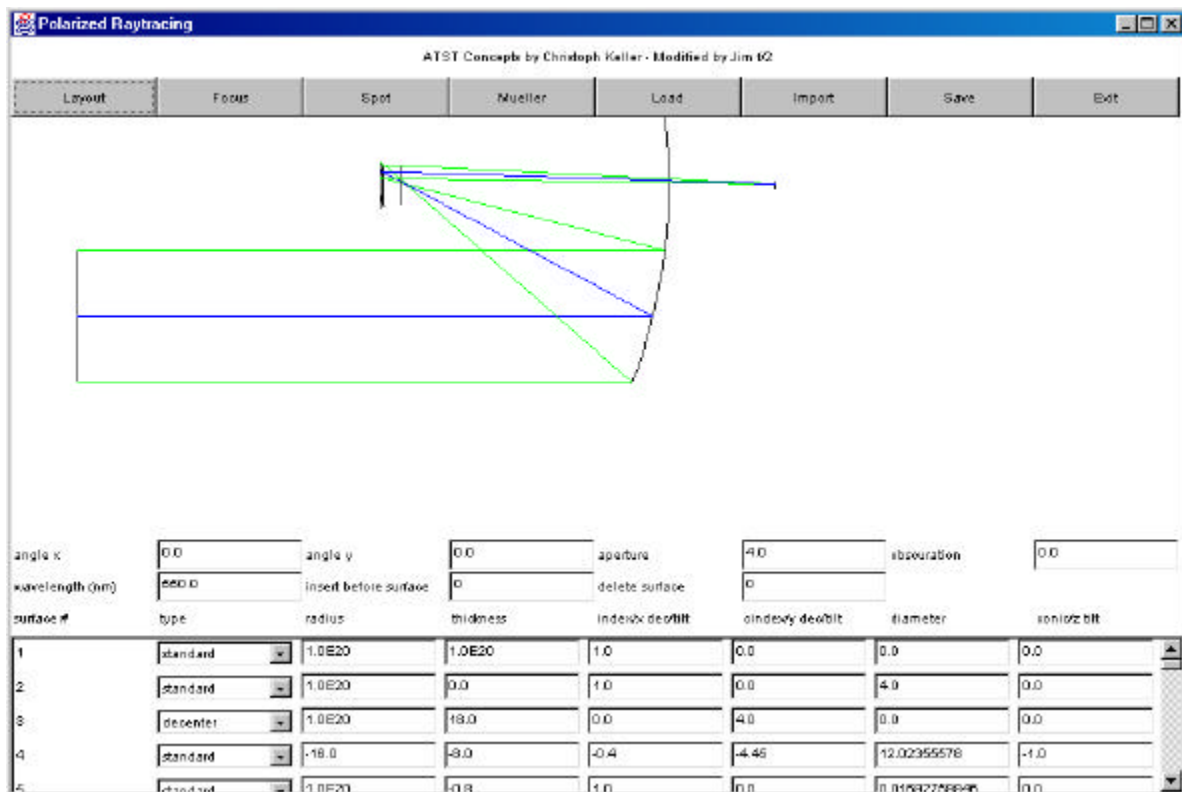


Figure 1. The $f/2$ configuration displayed by PolTrace.

Beams at the outer edge of the primary and secondary parents will therefore show considerably more instrumental polarization as compared to beams closer to the optical axis of the parents. To take this effect into account, 81 beams have been traced through the configuration and their respective Mueller matrices have been averaged. Figure 1 shows a side view of the $f/2$ primary mirror optical configuration using PolTrace.

3. MUELLER MATRICES

3.1 PRIMARY MIRROR F-RATIO

The first question to address concerns the Mueller matrices in the Gregorian focus as a function of the f -ratio of the primary mirror. The series of ZEMAX files prepared by Jim Oschmann (having an $f/30$ beam at the Gregorian focus) was used to calculate the Mueller matrices in the center of the field of view for bare aluminum coatings at 400 nm. For the $f/2$ configuration, the Mueller matrix in prime focus is given by

$$\begin{pmatrix} 1.0 & 0.002387 & 0.0 & 0.0 \\ 0.002387 & 0.999902 & 0.0 & 0.0 \\ 0.0 & 0.0 & -0.99955 & -0.02666 \\ 0.0 & 0.0 & 0.02666 & -0.999452 \end{pmatrix},$$

and the Mueller matrix in the Gregorian focus is given by

$$\begin{pmatrix} 1.0 & 0.004472 & 0.0 & 0.0 \\ 0.004472 & 0.999998 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.998424 & 0.049914 \\ 0.0 & 0.0 & -0.049915 & 0.998422 \end{pmatrix}.$$

As expected, the off-diagonal elements are about a factor of two larger in the Gregorian focus as compared to the prime focus. However, even in prime focus, the off-axis elements are large enough so that they need to be calibrated. Putting polarization optics in prime focus therefore does not provide a substantial advantage.

There are only two values in the Mueller matrices that are of importance. These are the I to Q and the V to Q crosstalks. Instead of showing the full Mueller matrices in the following, only these two Mueller matrix elements will be considered since they are sufficient to characterize the influence of the telescope on an incoming beam of light. Figure 2 shows these two crosstalks as a function of the primary mirror f -ratio.

As expected, the matrix elements scale almost exactly as the f -ratio squared. While the longer focal-length primary mirror concepts have smaller instrumental polarization, even an $f/3.75$ primary mirror still requires calibration of its instrumental polarization. While polarimetry favors a slow primary mirror, the fastest primary studied here ($f/2$) has instrumental polarization that is still acceptable, i.e. less than 1% I to Q cross-talk.

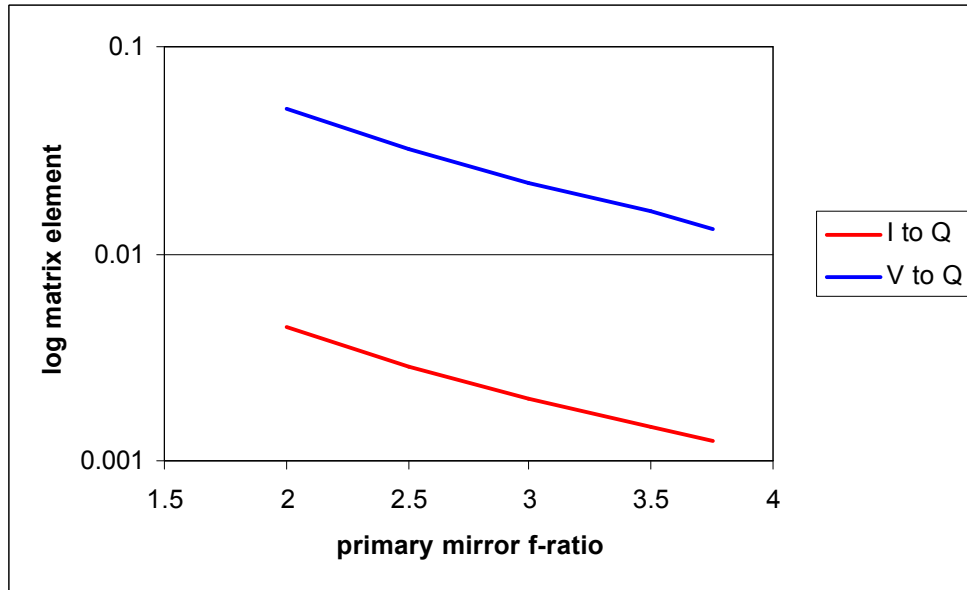


Figure 2. The I to Q and V to Q Mueller matrix elements in Gregorian focus as a function of primary mirror f-ratio at 400 nm for bare aluminum coatings.

3.2 WAVELENGTH VARIATION FOR F/2 PRIMARY MIRROR

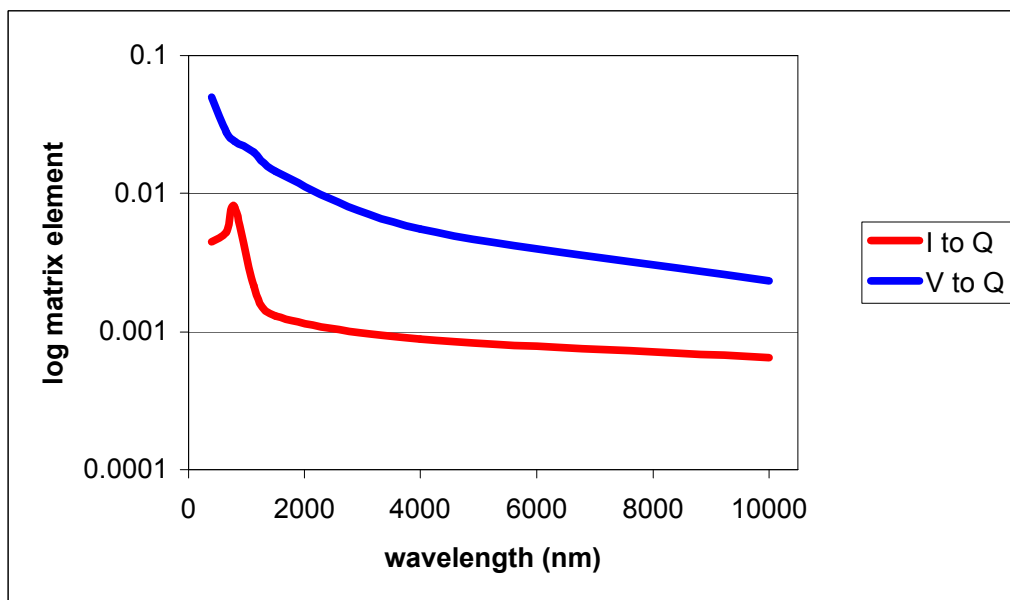


Figure 3. The wavelength variation of the $f/2$ primary mirror concept matrix elements for bare aluminum. It will be necessary to measure the instrumental polarization at all wavelengths because even at 10 μm the matrix elements are larger than what the science requirements demand.

3.3 FIELD-OF-VIEW VARIATION FOR F/2 CONCEPT

Another issue concerning instrumental polarization is its variation across the field of view. For an off-axis telescope, the field of view variation is not rotationally symmetric around its center. Therefore, consider

the variation along two axes: parallel and perpendicular to the axis of symmetry of the telescope. Together with the Mueller matrix for the center of the field-of-view, this leads to the following five matrices, arranged, as they would appear in the field of view. The off-center matrices have been calculated for an angular distance of 2.5 arcmin.

We recall that the center of the field of view has the following matrix:

$$\begin{pmatrix} 1.0 & 0.004472 & 0.0 & 0.0 \\ 0.004472 & 0.999998 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.998424 & 0.049914 \\ 0.0 & 0.0 & 0.049915 & 0.998422 \end{pmatrix}$$

Going parallel to the off-axis direction leads to

$$\begin{pmatrix} 1.0 & 0.004369 & 0.0 & 0.0 \\ 0.004369 & 0.999999 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.998455 & 0.048772 \\ 0.0 & 0.0 & -0.048772 & 0.998454 \end{pmatrix},$$

while going perpendicular to the off-axis direction leads to

$$\begin{pmatrix} 1.0 & 0.004318 & -0.000836 & -0.00002 \\ 0.004318 & 0.999946 & -0.000382 & 0.009329 \\ -0.000837 & -0.000163 & 0.998507 & 0.048196 \\ -0.00002 & -0.009336 & -0.048196 & 0.998453 \end{pmatrix}.$$

It is interesting to compare this to an on-axis Gregorian with the same f/2 primary mirror and f/30 Gregorian focus. At 2.5 arc minutes away from the center of the field of view, the Mueller matrix becomes

$$\begin{pmatrix} 1.0 & 0.000006 & 0.0 & 0.0 \\ 0.000006 & 0.999998 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.999988 & 0.000072 \\ 0.0 & 0.0 & -0.000072 & 0.999986 \end{pmatrix}.$$

The off-axis elements are all well below 10^{-5} , and therefore no calibration would be needed even at 2.5 arc minutes away from the center of the field-of-view.

4. CONCLUSIONS

The Mueller matrices presented in the last section are certainly more favorable than those of conventional solar telescopes such as the McMath-Pierce and the Dunn Solar Tower telescopes because of the almost normal incidence in the off-axis ATST concept. Compared to those facilities, ATST would have an advantage in terms of smaller instrumental polarization by about a factor of 5 to 10.

How does the ATST concept compare to THEMIS and the LEST concept, both of which have been optimized for low instrumental polarization? The dominant source of instrumental polarization in the

latter two projects is due to their entrance windows, i.e. birefringence due to mechanical and thermal stress. An estimate of the Mueller matrix for LEST at 500 nm is given by

$$\begin{pmatrix} 1.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.9980 & 0.0004 & 0.0113 \\ 0.0 & 0.0004 & 0.9980 & 0.0113 \\ 0.0 & 0.0113 & 0.0113 & 0.9960 \end{pmatrix}.$$

ATST with an aluminum coating is about a factor of 4 worse than the LEST concept and might be similar to THEMIS, which uses a much thicker window than the LEST design. However, the open-air, all reflective ATST design has the major advantage of a stable instrumental polarization as compared to the rapidly varying birefringence of a window.

There are a few points that have not been considered here in detail but that need to be kept in mind:

- The instrumental polarization rotates with respect to the solar image in the case of an alt-azimuth mount.
- Illumination changes on the primary and secondary mirrors will lead to changes in the instrumental polarization seen in the focal plane.
- The optical properties of the coatings will change (slowly) in time. The instrumental Mueller matrix will therefore change in time.